Large-Orbit Gyrotron Operation in the Terahertz Frequency Range

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Coherent terahertz high-harmonic radiation has been obtained in a gyrotron with an axis-encircling electron beam. An electron-optical system with a cusp gun and a following drift section of adiabatic magnetic compression with an area factor of 3000 provides the formation of an 80-keV/0.7-A beam of gyrating electrons in a wide range of voltages and magnetic fields. Stable single-mode generation with a power of 0.3–1.8 kW in microsecond pulses is detected at four frequencies in the range 0.55–1.00 THz at resonant magnetic fields 10.5–14 T.

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The maximum frequency of conventional gyrotrons has recently been increased up to 1.0–1.3 THz [1–3]. However, terahertz gyrotrons are not widespread yet since a very strong magnetic field is required for operation at the fundamental and second cyclotron harmonics. The magnetic field can significantly be decreased by using higher ($s \geq 3$) operating harmonics if the complicated problem of parasitic mode discrimination is solved. A significant mitigation of the problem is possible in a so-called large-orbit gyrotron (LOG) [4–9]. In this type of gyrotron, all electrons describe helical trajectories with the axes coinciding with the cavity axis or close to it (a monoaxial electron beam is used in this case instead of the polyaxial one employed in conventional gyrotrons). Because of such a beam configuration, the strongest coupling of the electrons with operating modes and a significantly better mode selectivity at high harmonics can be provided. In this way, powerful generation with a maximum frequency of 0.41 THz has already been demonstrated in a LOG with a 250-keV electron beam [9]. In this Letter, operation of a new third-harmonic LOG with a significantly higher operating frequency of up to 1 THz and with a more practical voltage of 80 kV is reported.

The efficiency of high-harmonic gyrotron generation can in principle be comparable with that at the fundamental cyclotron resonance, but higher cavity Q factors and electron currents are needed for the harmonic excitation. Actually, the starting current of a gyrotron with the traditional cylindrical cavity [Fig. 1(a)] depends on the main parameters as follows (see, e.g., [7]):

$$I_{\mathrm{st}} \propto \frac{1}{G_{m,s}\beta_{\perp}^{2s}(L/\lambda)^2 Q}. \qquad (1)$$

Here

$$G_{m,s} = \frac{J_{m-s}^2(\nu_{mp}R/a)}{(\nu_{mp}^2 - m^2)J_m^2(\nu_{mp})} \qquad (2)$$

is the excitation factor of the $\mathrm{TE}_{m,p}$ mode at the sth resonant cyclotron harmonic by a beam with the radius R of particle guiding centers, J_m and ν_{mp} are the Bessel function and the pth positive root of its derivative, respectively, a, L, and Q are the cavity radius, length, and total Q factor including both diffraction and Ohmic losses, $\beta_{\perp}$ is the rotational electron velocity normalized to the speed of light, and λ is the wavelength. In the case of weakly relativistic electrons where $\beta_{\perp}$ is essentially less than unity, the starting current rises with the harmonic number as $\beta_{\perp}^{-2s}$. This strong dependence can partially be compensated by an increase in the cavity length and diffraction Q factor. This possibility is limited, however, by Ohmic losses, which can, in turn, be somewhat diminished by operating at the modes with higher radial index p.

For a fixed cavity mode with a nonzero azimuthal index $m \neq 0$, the excitation factor described by Eq. (2) is maximum for the LOG configuration when an axis-encircling electron beam is used, $R = 0$, and the azimuthal mode index is equal to the harmonic number: $m = s$. In this case, the low-harmonic parasitic modes for which $|m - s| = 1$ and whose excitation factors rapidly increase as the electron guiding centers are slightly displaced from the cavity axis are most dangerous. The admissible displacement is of the order of 0.2λ.

The 1-THz third-harmonic LOG (Fig. 1) has been designed for operation at a relatively low voltage of 80 kV with an electron current of 0.7 A, a pulse duration of 10 μs, and a repetition frequency of 0.1 Hz. The magnetic field inside the cavity amounts to 13.7 T, whereas it is counterdirected and as small as -4.5 mT near the cathode. The magnetic field has been created by a water-cooled solenoid with a 4-ms pulse duration and a cathode coil [Fig. 1(c)]. A very high field compression allows a sufficiently high current density to be reached inside the operating cavity, while the emission density is not as high (4 A/cm^2). In order to decrease Ohmic losses, the operating mode $\mathrm{TE}_{3,7}$ with high radial index $p = 7$ was chosen. The corresponding diameter of the cavity is 2.3 mm. A relatively high pitch factor (1.4–1.5) and a long-length cavity (7.2 mm, or 24 wavelengths) are required to optimally excite this mode. A long length of the interaction region results in a

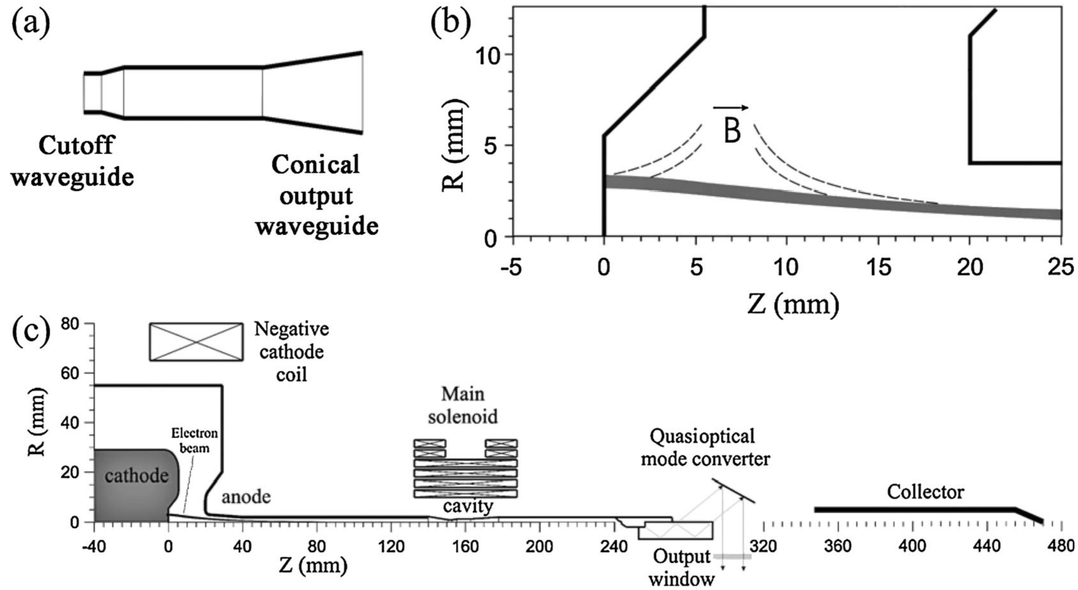


FIG. 1. The 1-THz third-harmonic LOG: cavity (a), cusp gun (b), and general scheme (c).

very narrow (compared with the experiment [9]) frequency band of the cyclotron resonance. According to calculations, this provides a sufficient mode separation (Fig. 2), such that the operating mode $TE_{3,7}$ should not be suppressed by the closest spurious second-harmonic mode $TE_{2,5}$ [Fig. 3(a)]. Simulations predict 1-THz operation at the operating mode with a fairly high (10%) electron efficiency. However, Ohmic losses decrease the total efficiency down to 1.3%, and, correspondingly, the calculated output power amounts to 0.7 kW.

One of the most complicated problems for realization of high-frequency LOGs is the creation of an electron-optical system forming an electron beam close to the axis-encircling one. This task cannot be solved in a conventional magnetron-injection gyrotron gun. For the studied 1-THz LOG, an electron gun with a cusp (reverse) of magnetic field [10,11] near the cathode [Fig. 1(b)] has been elaborated in order to provide an axis-encircling electron beam with admissible velocity and position spread of particles. The axisymmetric cusp gun is simpler for both calculation and realization (especially for future cw operation) than the Pierce-kicker guns used in most of our previous experiments with LOGs [7,9]. Because of the smaller initial electron density, such a gun ensures a smaller particle spread at a lower voltage and a higher operating frequency. In the designed gun, the electrons first go out rectilinearly from a ring emitter located in the axial magnetic field $B_1 = -4.5$ mT. The electrons' transverse velocity is seeded near the cathode, in the region of a sharp reverse of the magnetic field. Then the transverse velocity reaches the operating value by record compression in a magnetic field increasing 3000 times up to the operating value. According to simulations, a beam with current 0.7 A, pitch factor 1.5, and orbital velocity rms spread not more than 12% can be obtained in such a system.

The cusp gun was first tested in a specially simulated modeling regime. In the experiments, the chosen voltage 40 kV and cavity magnetic field 9.7 T were factors 2 and $\sqrt{2}$ less than the operating values, whereas the current was very small but sufficient for the fluorescence of a scintillat-

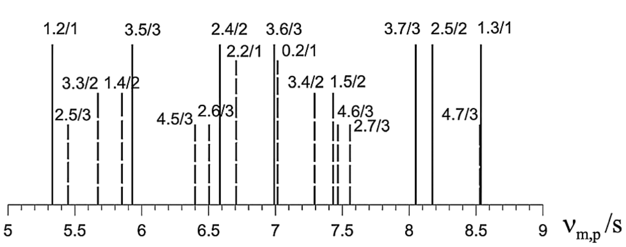


FIG. 2. The spectrum of potentially exciting cavity modes $TE_{m,p}$ (contracted notations m.p/s are used for the excitation at the sth cyclotron harmonic; the value $\nu_{m,p}/s$ is proportional to the resonant magnetic field).

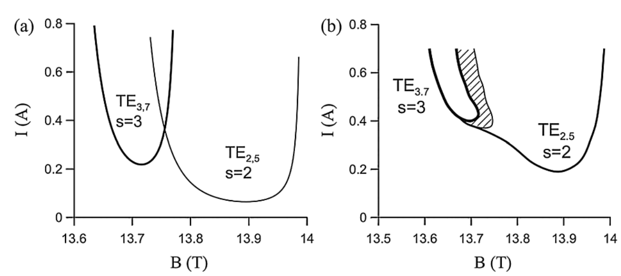


FIG. 3. Calculated (a) and experimentally observed (b) regions of excitation for the operating third-harmonic mode $TE_{3,7}$ and closest spurious second-harmonic mode $TE_{2,5}$ in the 1-THz LOG (two-frequency generation was observed in the shaded area between the regions of the $TE_{3,7}$ and $TE_{2,5}$ modes).

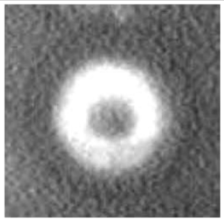
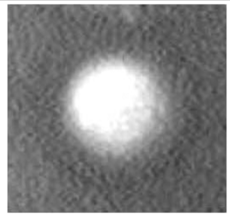
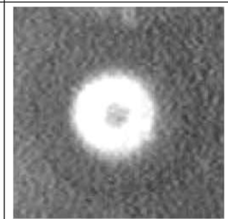
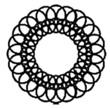
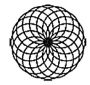
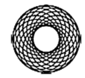
Magnetic field at the cathode	$B_1 > 0$	$B_1 = 0$	$B_1 < 0$
Beam trace at the scintillating target			
Simulations			

FIG. 4. Low-current modeling of the cusp gun for the 1-THz LOG: electron beam traces on the scintillating target and calculated electron trajectories for positive, zero, and negative magnetic fields at the cathode.

ing target. Three types of beam traces were observed on the quartz target for different values and signs of the cathode magnetic field B_1 (Fig. 4). These results correspond very well to Busch's theorem, which gives the following expression for the electron Larmor radius after the transition of a single particle through a fast jump of the axisymmetric magnetic field:

$$r = r_c \frac{B_2 - B_1}{2B_2}. \tag{3}$$

Here r_c is the radius of the electron emitter, and B_2 is the magnetic field in the region after the field reversal. In the first regime, in which the fields of the cathode coil and the main solenoid were codirected (the cusp was absent), a ring-type spot was observed on the target; this corresponded to a polyaxial tubular beam. A decrease in $|B_1|$ resulted in an increase in the Larmor radii. Simultaneously, the electron guiding centers were shifted to the center of the beam. When the cathode field was equal to zero, a regime with large rotational velocities was observed. In this case, the radius of the electron guiding centers was close to the Larmor radius, so that the electron orbits filled in almost the whole cross section of the beam. In the third regime, B_1 was negative, so that the cusp was realized. In this case, an increase in $|B_1|$ led to an increase in the electron Larmor radius and a decrease in the radius of the guiding centers. In an ideal case of sharp and symmetric cusp, i.e., for $|B_1| = B_2$, an axis-encircling electron beam should be provided. The measured displacement of the guiding centers was almost twice smaller than the Larmor radius.

In a full-scale experiment with the 1-THz LOG, the new cusp gun properly operated for currents of up 0.7 A in wide ranges of voltage (50–80 kV) and magnetic field (10.5–14 T). Correspondingly, a high-frequency generation could be observed not only at the designed third-harmonic mode $TE_{3,7}$ but also at three other modes resonant both at the second and third cyclotron harmonics. As consistent with calculations [Fig. 3(a)], the zone of excitation for the chosen operating mode $TE_{3,7}$ was slightly restricted on the part of large magnetic fields and/or low voltages because of the excitation of the mode $TE_{2,5}$ [Fig. 3(b)]; the same mode was also always excited during the voltage rise and fall times (Fig. 5). For the cavity with a fairly well-known radius, mode identification could be performed by measurement of radiation frequencies and resonant magnetic fields. The frequency was roughly measured by a set of filters with cutoff frequencies 0.29, 0.4, and 0.8 THz. A stable single-mode operation was observed for the second-harmonic modes $TE_{2,4}$ and $TE_{2,5}$, as well as for the third-harmonic modes $TE_{3,6}$ and $TE_{3,7}$. The frequency of the $TE_{2,4}$ mode, which is equal to 0.545 88 THz, was measured with high accuracy using a semiconductor mixer and a frequency synthesizer. After that, the calculation yielded the frequencies 0.68, 0.87, and 1.00 THz for three other modes $TE_{2,5}$, $TE_{3,6}$, and $TE_{3,7}$, respectively. The power at the output of the quasioptical mode converter, which trans-

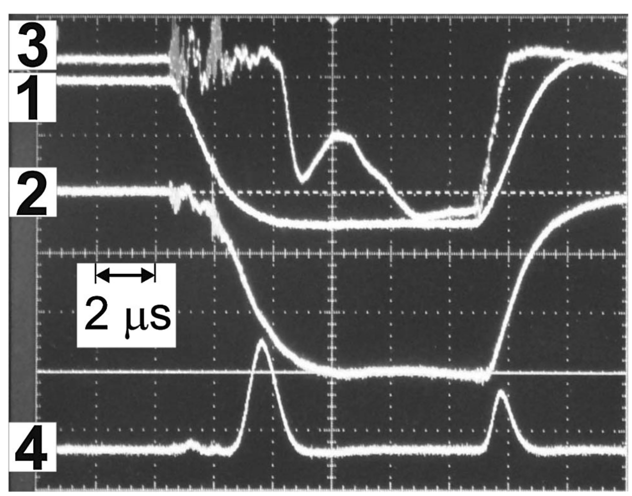


FIG. 5. Oscilloscope traces: pulse voltage (1) and current (2), detector signals for the $TE_{3,7}$ (3) and $TE_{2,5}$ (4) modes.

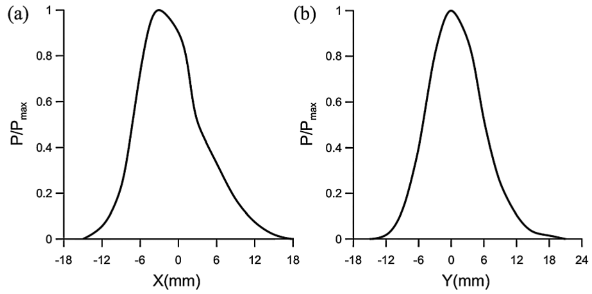


FIG. 6. Horizontal (a) and vertical (b) distributions of radiated power at a distance of 160 mm from the output window for an operating frequency of 1 THz.

formed all of the modes into Gaussian wave beams (see, e.g., Fig. 6), was measured calorimetrically in several pulses with an accuracy of about 20%. The measured power for different values of the voltage and magnetic field was 0.6, 1.8, 0.3, and 0.4 kW for the modes $TE_{2,4}$, $TE_{2,5}$, $TE_{3,6}$, and $TE_{3,7}$, respectively. The corresponding efficiency was about 2.2%, 3.5%, 0.9%, and 0.7%, respectively.

Thus, the high-harmonic LOG was operated for the first time at frequencies of up to 1 THz. It is important that this was achieved for relatively low electron energy and magnetic field. This can provide sources for powerful radiation over the entire terahertz frequency range, which makes them convenient and available for many promising applications.

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