Generation of 1.5-kW, 1-THz Coherent Radiation from a Gyrotron with a Pulsed Magnetic Field

M. Yu. Glyavin, A. G. Luchinin, and G. Yu. Golubiatnikov
Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia

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To cover a so-called terahertz gap in available sources of coherent electromagnetic radiation, the gyrotron with a pulsed solenoid producing up to a 40 T magnetic field has been designed, manufactured, and tested. At a 38.5 T magnetic field, the gyrotron generated coherent radiation at 1.022 THz frequency in 50 μ sec pulses. The microwave power and energy per pulse were about 1.5 kW and 75 mJ, respectively. Details of the gyrotron design, manufacturing, operation and measurements of output radiation are given.

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Development of compact, simple, and reliable sources of terahertz (THz) radiation is important for numerous applications, which include plasma diagnostics [1], electron-spin resonance spectroscopy [2], enhancement of NMR sensitivity using dynamic nuclear polarization [3], standoff detection and imaging of explosives and weapons [4], new medical technology [5], atmospheric monitoring [6], chemical technologies, and production of high-purity materials. Some issues in using of THz sources have been recently discussed in the review papers [6,7]. Today there are known solid-state [7] and vacuum electron sources [8] delivering THz radiation at power levels from milliwatt to tens (and even hundred—in the case of quantum cascade lasers [9]) milliwatt. Vacuum electron devices, in which electrons interact with fast waves (free electron lasers [10] and masers [11]) can deliver much higher power levels. However, typically these devices utilize relativistic electron beams and, hence, require large-size charge particle accelerators. Gyrotrons based on the interaction of electrons gyrating in external magnetic fields with fast waves [11] can utilize electron beams with voltages below hundred kV. These devices are much more compact than free electron lasers because they do not require large accelerators or high-voltage modulators. However, to provide cyclotron resonance between gyrating electrons and fast waves excited in smooth waveguides at THz frequencies near cutoff, high magnetic fields are necessary: in the range of 40 T for the fundamental harmonic interaction; at higher harmonics the magnetic field decreases inversely proportional to the cyclotron harmonic number. Typically, magnetic fields, which can be produced in cryomagnets with a large enough inner bore, do not exceed 15–20 T. The gyrotrons designed for second harmonic operation produced several tens of watts at frequencies up to 0.89 THz in the cw operation regime [12]. Higher magnetic fields can be realized with the use of pulsed magnets. Below we present results of the design, manufacturing, and experimental test of a gyrotron with a pulsed magnetic field where coherent 1 THz radiation was produced at 1 kW power level.

A compact (total length 400 mm), demountable THz gyrotron tube with a pulse magnet has been designed, constructed and tested at IAP RAS. This work is based on the previous results obtained with gyrotrons using pulsed solenoids [13] and on the development of an improved pulsed solenoid, producing up to 40 T magnetic field [14]. A gyrotron photo is shown in Fig. 1 and a block diagram of the experimental facility is shown in Fig. 2. In the design of this gyrotron a number of specific requirements for gyrotrons operating with pulsed magnetic fields were taken into account. First, to provide the cyclotron resonance condition accurately enough, the magnetic field should be reproducible from pulse to pulse and its value during the microwave radiation pulse should vary by less than 0.1%. Second, conductivity of a resonator wall should meet contradicting requirements: on the one hand, this conductivity should be rather poor to allow the varying magnetic field to penetrate into the resonator; on the other hand its inner surface should have conductivity high enough to provide reasonably low levels of Ohmic losses. Then, as in conventional gyrotrons, the magnetic field

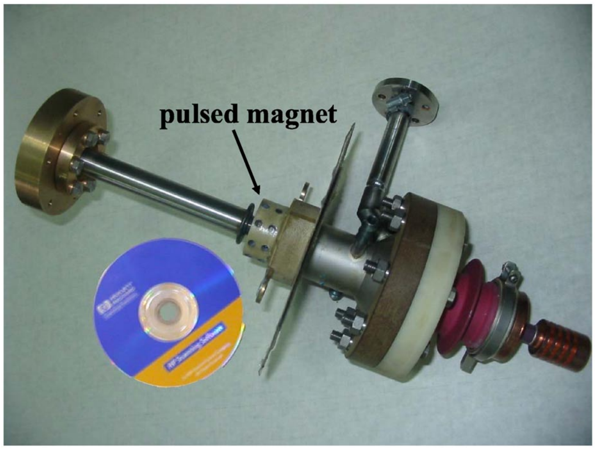

FIG. 1 (color online). Photo of the gyrotron with pulse solenoid producing 40 T magnetic field Electron gun is on the right and the output window is on the left.

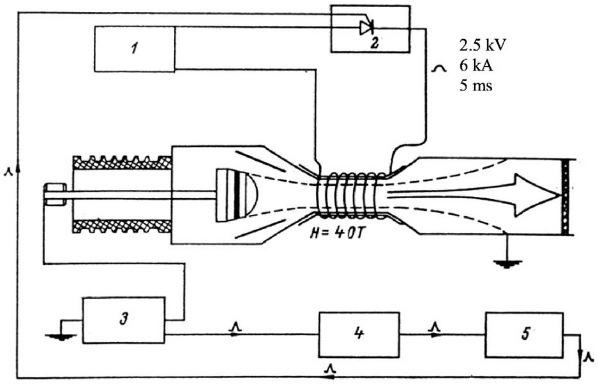

FIG. 2. Block diagram of the experimental facility: 1: capacitor bank, 2: thyristor switch, 3: high-voltage power supply, 4: delay unit, 5: control unit.

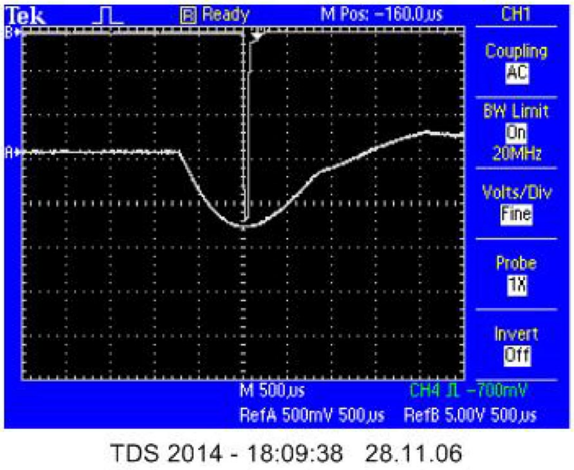

FIG. 3 (color online). The high-voltage pulse (50 μs) synchronized with the peak of the pulsed magnetic field. Horizontal scale is 500 μs per division.

distribution on axis should be uniform in the interaction space. Finally, the tube and the solenoid should be robust enough to withstand mechanical stresses caused by high pulsed magnetic fields.

The solenoid was made of a composite cable consisting of a 40%Nb-60%Ti alloy mechanically reinforced in an outer copper shell. For reducing Ohmic heating and stabilizing the operation, the solenoid was cooled by liquid nitrogen, which reduces the resistance by a factor of 7 in comparison with the room temperature resistance. The cable was wired directly on a thin stainless steel gyrotron body. This allowed for significant reduction of the solenoid inner bore diameter (up to 6 mm) and the energy required for obtaining the necessary magnetic field. The magnetic field was produced in the course of discharge of a bank of capacitors. The voltage and the coil current in 1.5 ms pulses did not exceed 2.5 kV and 6 kA, respectively, (total storage energy was about 5.6 kJ). The pulse-to-pulse reproducibility of the magnetic field was within 0.05%. Because of limitations caused by cooling the pulsed solenoid, the repetition rate was limited by one shot in a minute. After more than 2500 pulses with magnetic fields above 30 T no signs of solenoid deterioration had been observed.

Gyrotron components included the conventional cylindrical cavity (3 mm diameter and 3 mm length of a straight section) and the diode-type magnetron injection gun (accelerating voltage 20–25 kV, beam current up to 5 A, pulse duration 50 μs). The cavity was made of beryl bronze; its diffractive and Ohmic Q were estimated as 2500 and 8200, respectively. The high-voltage pulse was synchronized with the peak of the pulsed magnetic field as shown in Fig. 3.

Experimental results were obtained for high frequency operation at the fundamental cyclotron resonance. Detection of microwave power was made by a silicon point contact diode and by the dummy load. In our experiment, the calorimeter described in Ref. [15] was used, which has the sensitivity allowing for detecting the microwave energy in single shots at a 10 mJ level. By varying the magnetic field, a number of various modes with frequencies close to 1 THz and the output power at about 1 kW level were excited in a step-tunable manner (this step tunability was described elsewhere [16]). At the magnetic field close to 38.5 T, the transverse-electric (TE17,4) mode was excited at 1.022 THz frequency. The microwave pulse of this mode is shown in Fig. 4. The radiation power averaged over the pulse was 1.5 kW. This power level for a 24 kV, 3 A electron beam corresponds to 2.2% output efficiency. From the relation between diffractive and Ohmic quality factors it follows that this value corresponds to the interaction efficiency (for a reasonable value of the orbital-to-axial velocity ratio about 1.2–1.3) of about 5%. The main

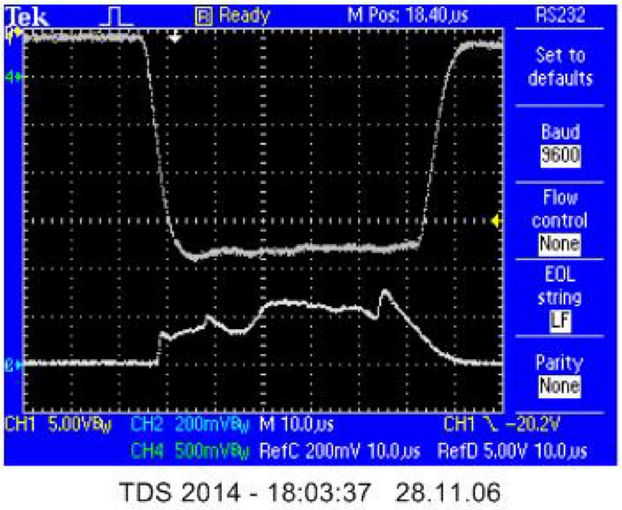

FIG. 4 (color online). The microwave pulse of the $\mathrm{TE}_{17,4}$ operating mode. Upper trace—high-voltage pulse, lower trace—microwave signal from detector. Horizontal scale is 10 μs per division.

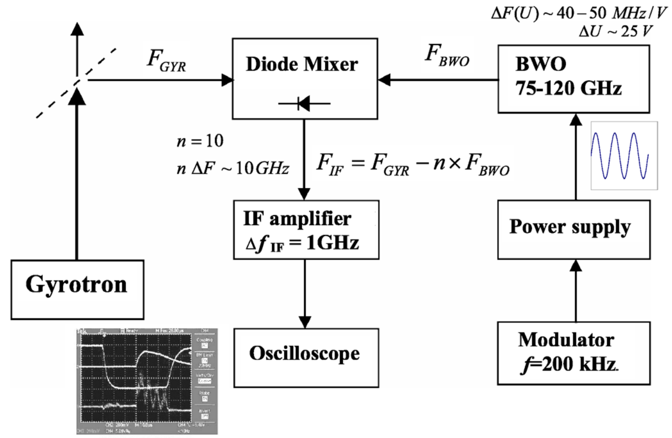

FIG. 5 (color online). Block diagram of the frequency measurement section of the experimental setup and example of oscilloscope trace.

reason for a relatively low efficiency is the cavity length which is about 2 times longer than the optimal one. However, in a gyrotron with so long cavity the start current is much lower than the beam current that ensures the excitation of the desired mode.

To measure the THz frequency in a device operating in single shots is a serious problem because of the absence of standard instruments. Our method was based on mixing the gyrotron signal with the signal from a millimeter-wave frequency synthesizer. The block diagram of the frequency measurement section of the experimental setup is shown in Fig. 5. Our method is quite close to the one described in [17]. The distinction is in the fact that in our experiment the gyrotron frequency was slightly varied from pulse to pulse. Therefore, to get the intermediate frequency (IF) in a relatively narrow frequency band of the IF amplifier (1 GHz) the frequency of the backward-wave oscillator (BWO) shown in Fig. 5 was swiped during the microwave pulse several times. Then, by gradually narrowing the bandwidth of BWO frequency modulation it was possible to determine the radiation with the precision determined by the bandwidth of the IF amplifier given above. The measured frequency 1.022 THz was close to the cyclotron frequency defined by the magnetic field which is equal to 1.024 THz. Brief estimation of the frequency bandwidth based on experimental data is about 10 MHz and a detailed analysis of the frequency spectrum will be carried out soon.

So, in the experiment with gyrotron operating in pulsed magnetic field, coherent THz radiation with the microwave power of 1.5 kW and the microwave energy 75 mJ in single shots was obtained for the first time. There are some plans to developed similar gyrotrons with improved solenoid cooling allowing for operation with higher repetition rate [18].

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