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DEVELOPMENT AND EXPERIMENTAL INVESTIGATIONS OF HIGH POWER PULSED THZ GYROTRONS

The terahertz radiation looks promising for pointer plasma discharge, remote detection of concealed radioactive materials, plasma diagnostics based on collective Thompson scattering, enhancement of spectroscopy methods, new medical technology and so on. The aim of our investigations is development of powerful and relatively compact microwave sources. Powerful THz generation has been demonstrated in pulse gyrotrons. Pulsed coils with field intensity up to 50 T have been developed and tested. This field gives a chance to operate at fundamental cyclotron resonance conditions between electron beam and operating mode and, as result to simplify problem of mode selection. The output power 5 kW at 1 THz and 0.5 kW at 1.3 THz has been obtained with pulse duration 40 µs at the fundamental harmonic with 30 kV/5A electron beam. The power 200 kW at the frequency 0.67 THz has been realized with efficiency about 20 %. Despite the requirement of strong operating magnetic fields, the THz frequency has been achieved by the pulse gyrotrons operating at the fundamental harmonic. Today it is clear that relatively small-size tubes with a high level of output power (from a hundred to several kilowatts) at the frequencies of 0.3–1.5 THz will be available soon for many applications. Fig. 7. Ref.: 13 titles.

Key words: terahertz, kW, gyrotron, pulsed solenoid.

Terahertz frequency range (0.1–10 THz), which occupies an intermediate position in the electromagnetic spectrum between the microwave and optical ranges, has a number of specific features that make it very attractive for a wide range of fundamental and applied researches in physics, chemistry, biology and medicine. Development of compact, simple and reliable sources of THz radiation is important, in particular, for plasma diagnostics based on collective Thompson scattering, remote detection of concealed radioactive materials, enhancement of spectroscopy methods, development of multi-charged ion beams for nano-litograthy and so on [1, 2]. One of the most promising powerful generators of THz radiation is gyrotron (see, for example, reviews [3, 4]). The general view of a gyrotron is shown in Fig.1. Such devices are a variety of cyclotron resonance masers (CRM), which based on the mechanism of coherent cyclotron radiation from electrons gyrating in a constant magnetic field. In these devices, the electrons can resonantly interact with fast waves, which, in principle, can propagate even in free space. Therefore, the interaction space in gyrotrons can be much larger than in classical microwave tubes operating at the same wavelength, so gyrotrons can provide much higher power than solid-state and classical vacuum electronics sources. In comparison with Free Electron Lasers (FEL), gyrotrons can operate with electron beams having significantly lower energies and are much more compact than FELs.

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. In principle, efficient operation can be obtained at high cyclotron harmonics, but special methods of mode selection (electrodynamics, as, for example step cavities, or electronics, as axis-encircling beams) are needed for single mode excitation of operating mode at harmonics. The harmonic operation is very attractive, because it requires a weaker operating magnetic field which is inversely proportional to the harmonic number, but mode selection and high ohmic losses take many efforts to overcome. However, realization of high-harmonic short-wave high intensity magnetic fields, reasonable for fundamental harmonic operation, can be realized with the use of pulsed non-destructible coils.

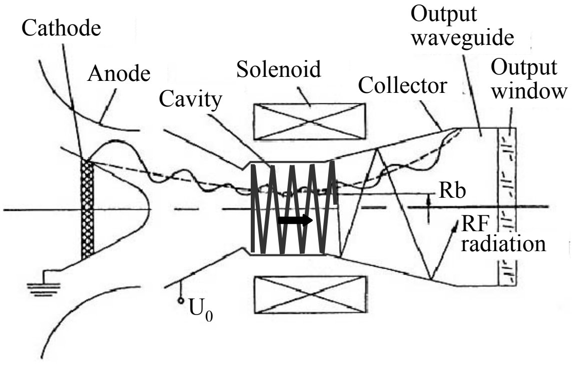


Fig. 1. Schematic view of a gyrotron

In recent years, IAP RAS vacuum electronics move though magic 1 THz mark, which was a 40 years goal for gyrotron society. In recent experiments, gyrotron based on a pulse solenoid with magnetic field intensity up to 50 T generated a power of 5–0.5 kW at the fundamental cyclotron resonance in a single pulse operation regime with pulse duration about 50 µs at world record frequencies 1–1.3 THz [5, 6]. The power 200 kW at the frequency 0.67 THz has been realized with efficiency about 20 % [7]. For the purpose of achieving high resolution in strong-field

NMR spectroscopy by using dynamic nuclear polarization (DNP/NMR spectroscopy), IAP has created a gyrotron complex based on a CW gyrotron with a frequency of 0.26 THz and a power of 100 W at the second cyclotron harmonics, which ensures high stability of frequency and generation power, equal to $3 \cdot 10^{-6}$ and 10^{-2} correspondingly, during 12 hours of operation. The experiments with the use of this generator performed at the Institute of Biophysical Chemistry of Goethe University (Frankfurt-am-Main, Germany) allowed increasing the sensitivity and resolution of the NMR spectrometer by 80 times [8]. In large-orbit gyrotrons (LOG), single mode generation with a power 0.3–1.8 kW in repetition rate (0.1 Hz) regime with pulse duration of 10 μs was obtained in the range from 0.55 to 1 THz at the second and third cyclotron harmonics [9]. The permanent-magnet LOG based on a permanent magnet with field intensity 1.7 T developed by IAP jointly with foreign partners made it possible to achieve generation from the 3rd to 5th harmonics at frequencies up to 0.14 THz [10].

Below we present results of the design and results of experimental tests of series of fundamental harmonic pulsed gyrotrons where coherent THz range radiation was produced.

1. Design and experimental tests of fundamental harmonic 1 THz gyrotron. 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 [11] and on the development of an improved pulsed coil. Gyrotron photo and block diagram of the experimental facility is shown in Fig. 2, 3, correspondingly.

Fig. 2. Fundamental harmonic THz range demountable gyrotron with pulsed solenoid

In the design of terahertz gyrotron a number of specific requirements for gyrotrons operating with pulsed magnetic fields were taken into account. First, to provide cyclotron resonance condition accurately enough, magnetic field should be reproducible from pulse to pulse and its value during the high voltage 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 varying magnetic field to penetrate into the resonator; on the other hand its inner surface should have conductivity high enough to provide reasonably low level of ohmic losses. Then, as in conventional gyrotrons, magnetic field distribution on axis should be uniform in the interaction space. Finally, the tube and the solenoid should be robust enough to sufficient mechanical stresses caused by high pulsed magnetic fields.

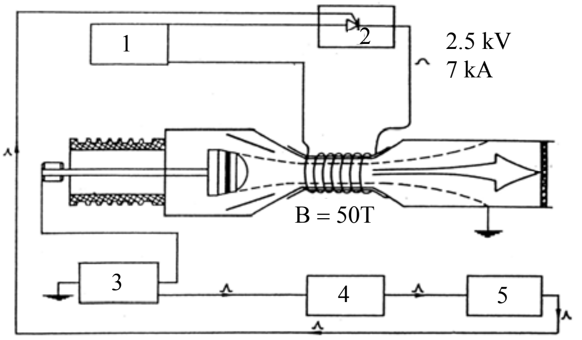


Fig. 3. Block diagram of experimental facility for pulsed magnetic gyrotron tests: 1 – capacitor bank; 2 – thyristor switch; 3 – high voltage power supply; 4 – delay unit; 5 – control unit

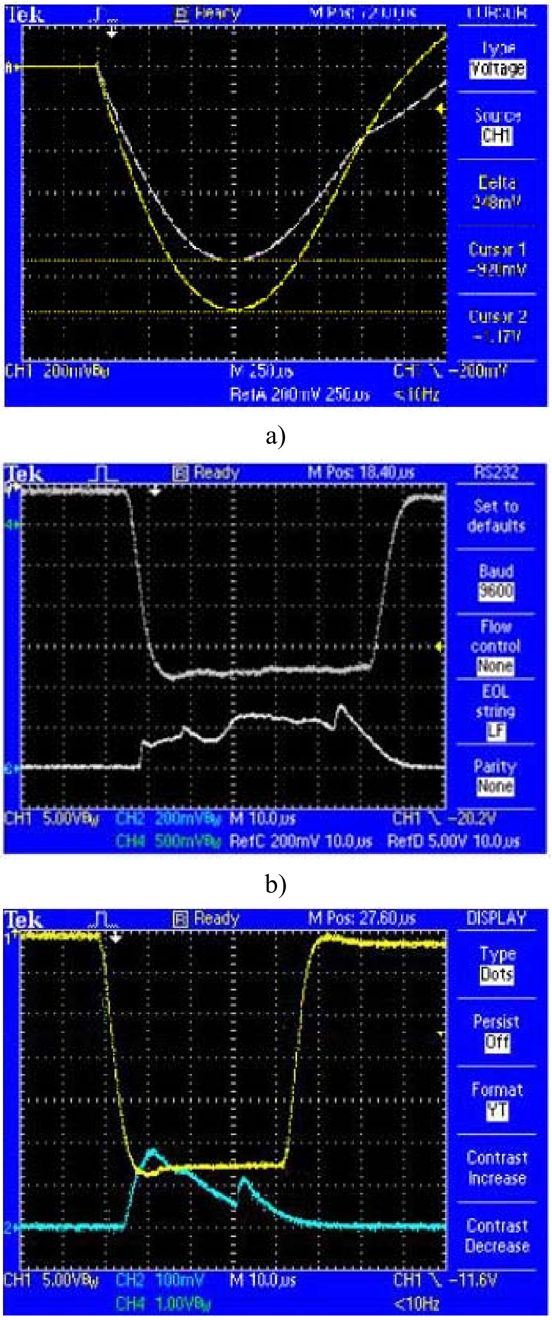
The solenoid was made of a composite cable consisting of a 40 %Nb–60 %Ti alloy mechanically reinforced in an outer copper shell. For reducing ohmic heating and stabilizing the operation, the solenoid was cooled by liquid nitrogen, which reduces the resistance by a factor of 7 in comparison with the room 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. Magnetic field was produced in the course of discharge of a bank of capacitors. The maximum coil current in 1.5 ms pulses was 7 kA (capacitors voltage 2.5 kV, storage energy about 7.6 kJ). The pulse-to-pulse reproducibility of the magnetic field was within 0.05 %. Due to limitations caused by cooling the pulsed solenoid, the repetition rate was limited by one shot in a minute for 40 T magnetic field operation and one shot in a three minute for 50 T field. After more than 3 500 pulses with magnetic fields above 35 T no signs of solenoid deterioration have been observed.

Gyrotron components included the conventional cylindrical cavity (3 mm diameter) 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 2 500 and 8 200, respectively. The high-voltage pulse was synchronized with the peak of the pulsed magnetic field.

Experimental results were obtained for high frequency operation at the fundamental cyclotron resonance. The microwave power was detected by a silicon point contact diode and by the dummy load, which has the sensitivity allowing for detecting the radiation energy in single shots at a 10 mJ level. To measure the THz frequency in single-shot operation regime the method based on mixing the gyrotron signal with the signal from a millimeter-wave frequency synthesizer has been used. 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) was swept 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. By varying the magnetic field, a number of various modes with frequencies close to 1 THz were excited in a step-tunable manner [5]. Two cavities with variable length of a straight section (3 and 2 mm) and a series of cathodes differing by the quality of emission area were tested. The maximum output power was measured at the frequency 1.02 THz. The radiation power averaged over the pulse was 5 kW. This power level for a 27 kV/ 3 A electron beam corresponds to 6.1 % output efficiency. The highest generation frequency 1.3 THz was observed at magnetic field about 50 T with power averaged over the pulse about 0.5 kW. Oscilloscope trace of solenoid current for 1 and 1.3 THz operation regime and corresponding detector signals are shown in Fig. 4.

2. Development of compact sub-THz sub-MW repetition rate regime gyrotron. To increase output power the sub-MW level fundamental harmonic gyrotron with operating frequency about 0.33 GHz was designed based on improved solenoid with field intensity up to 15 T and repetition frequency up to 1 Hz. The solenoid consists of 10 sections with independent water cooling and for pulse duration about 2.5 ms the repletion rate about 1 Hz was obtained. The calculated gyrotron efficiency at fundamental harmonic for helical electron beam with voltage 70 kV, current 60 A and transverse energy 0.6 from total energy closed to 0.25. The preliminary gyrotron test demonstrated single mode operation at power level close to calculated one, but coil strength is not enough for repetition rate regime (life time about two weeks) and needs future optimization.

3. Powerful 0.67 THz gyrotron. Based on success of high frequency pulsed gyrotron experiments, gyrotron for initiations of pointer plasma discharge was proposed. Recently, a new possible application of powerful sources of sub-THz radiation has been suggested [12]. In brief, this application is aimed at remote detection of concealed radioactive materials with the use of high-power sub-THz radiation.



a)

b)

c)

Fig. 4. Oscilloscope trace of solenoid current for 40T and 50T field (a); microwave power and high voltage for 1 THz (b) and 1.3 THz (c) operation regimes

As it is known, even shielded radioactive materials may emit gamma rays through the walls of any container, and these gamma rays cause ionization of air molecules. It is also known that high-power electromagnetic radiation being focused in a spot of the wavelength scale can exceed the breakdown threshold. Therefore, when there are some seed free electrons in such a breakdown-prone volume, the breakdown may take place there. An ambient electron density is usually estimated to be at the level of 1 electron per cubic cm, although there are some reservations about these numbers. When the wavelength is short enough and the wave power is high enough, one can realize conditions for a low breakdown rate in the absence of radioactive materials low, but high breakdown rate in their presence. It was shown that an attractive option would be a 0.67 THz gyrotron delivering the power above 200 kW in 10-20 μs long pulses. The choice of the frequency was determined by two factors. First, at this frequency there is an atmospheric "window" with relatively low propagation losses of 50 dB/km, i. e. wave attenuation is less than 3 dB at distances of 20–40 m. Second, this frequency is close to the electron-molecule collision frequency at 1 atm., i. e. it corresponds to the bottom of the Paschen curve.

Other application of powerful pulsed THz range gyrotron can be initiations of pointer plasma discharge. Study of the self-sustained and initiated discharges by using the gyrotron radiation was made in the wide range of pressures (0.01–1 500 Torr) in different gases (helium and argon). Self-sustained discharge could be maintained in the pressure range from 20 Torr to 2 atm. By using the several methods of discharge initiation it was possible to expand the range of discharge existence to the pressure value of about 0.01 Torr. It was shown that the low pressure (dozens of Torr and less) discharge has a number of features compared with the discharge of high pressure: the presence of the powerful afterglow with length of about 20–50 μs after gyrotron pulse, the lack of a strongly inhomogeneous spatial structure of the discharge glow (at pressures less than 10 Torr), the lack of screening of the discharge appearance location from the gyrotron radiation. The size of the discharge plasma at pressure value of 0.01 Torr was about 1 mm (Fig. 5). Such a discharge can be used as the pointed source of multi-charge ions [13], especially for generation UV radiation, including the projection lithography.

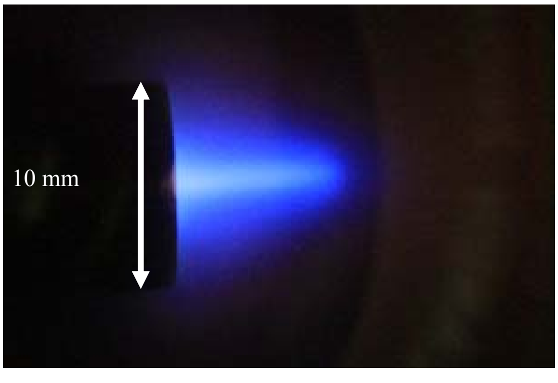


Fig. 5. Discharge in Ag gas at 0.01 Torr pressure, initiated by focused gyrotron radiation at frequency 0.67 THz

Let us present a key data about gyrotron design and experiments. To avoid significant ohmic losses of the radiated power in the circuit walls it was decided to operate in a high-order $TE_{31,8}$-mode whose ability to operate stably at a megawatt level was recently demonstrated in a 0.17 THz gyrotrons developed for plasma experiments in ITER. Preliminary analysis of a 0.67 THz gyrotron operating in this mode showed that the ohmic Q-factor of a copper cavity can be as high as 30 000, while the cavity diffractive Q responsible for the outgoing sub-THz radiation does not exceed 3 000. So, the ohmic losses should be less than 10 % of the radiated power, while in devices such as, for example, extended interaction klystron even in the W-band (95 GHz) ohmic losses are at a 1/3 level of the power radiated by an electron beam. Design of a gyrotron cavity was under the assumption that oscillations can be excited by a 70 kV, 15 A electron beam with the orbital-to-axial velocity ratio of 1.2–1.3. The chosen cavity radius was equal to 4.54 mm, which corresponds to operation in the $TE_{31,8}$-mode at the 0.67 THz frequency. The electron beam radius was equal to 2.3 mm, which corresponds to the maximum beam coupling to this mode co-rotating with electrons gyrating in the external magnetic field. The cavity profile was found to yield 35 % interaction efficiency even in the presence of electron velocity spread. To run a 0.67 THz gyrotron at the fundamental cyclotron resonance one should have the magnetic field about 27 T. Such field can be produced by a pulse solenoid similar to those used in previous experiments [5, 6]. To provide penetration of a variable magnetic field inside a gyrotron, the duration of the magnetic pulse was programmed to be about 2 ms and the gyrotron body was made of a 1 mm thick stainless steel. Two versions of gyrotron cavities were fabricated and tested: one from bronze and another from stainless steel with inner coating by a 10 μm thick layer of copper (at this frequency, the skin depth in copper is less than 1 μm).

The demountable gyrotron tube with a pulse magnet was manufactured by IAP/GYCOM in accordance with the above design requirements. Two identical tubes were made and independent experiments have started at IAP RAS and University of Maryland (Maryland, USA) [13, 14]. The solenoid was made of a rectangular copper cable, wired directly on a thin stainless steel gyrotron body. The solenoid was cooled with liquid nitrogen to reduce ohmic heating and have reproducible shot-to-shot operation. The operating magnetic field (coil current) decided based on the calibration made by Hall-effect device in a low-field CW regime. The voltage and the coil current did not exceed 3.5 kV and 7 kA, respectively; total stored energy was about 20 kJ. The pulse-to-pulse reproducibility of the magnetic field was within 0.05 %. Due to the limitation of the pulsed solenoid cooling time, pulse-to-pulse reproducible results were obtained with the repetition rate not exceeding one shot in 3 min.

Experimental results were obtained for 0.5–0.7 THz operation at the fundamental cyclotron resonance at several operating modes. Detection of microwave power was made by a silicon point contact diode and by a dummy load. In the experiments original dummy loads were used. The sensitivity allowing for detecting the microwave energy in single shots are at a 10 mJ level and above. The magnetic field was varied for maximizing the output power and efficiency. Gyrotron photo, and schematic drawing are shown in Fig. 6; typical oscilloscope traces of high voltage, beam current and microwave signal are shown in Fig. 7.

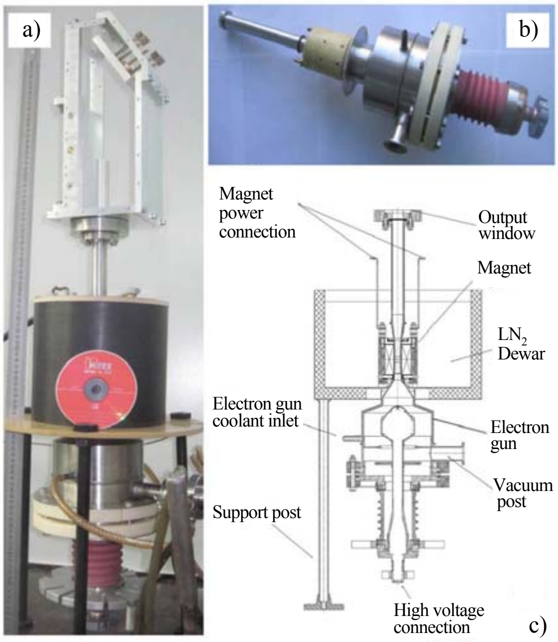


Fig. 6. Gyrotron photos (a, b) and scheme (c)

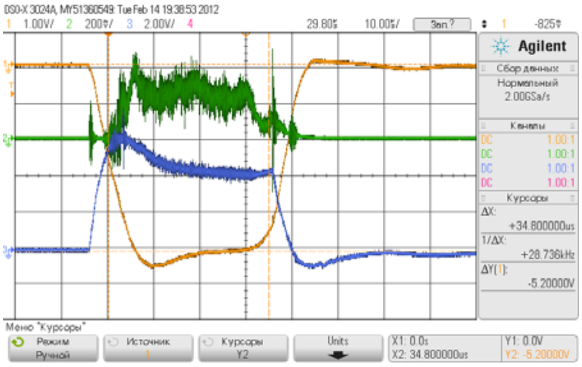


Fig. 7. Typical oscilloscope traces of high voltage (CH1), beam current (CH3) and microwave signal (CH4). The noise on microwave signal resulting from external pickups

As it was mentioned above, in the experiments, two types of cavities had been used: first, the bronze and, then, the stainless steel with a thin internal copper layer coating. The length of a straight section was varied from 4 to 6 mm for both materials. In experiments with the bronze cavity it was found that the maximum power realized in a 4 mm long cavity is close to 100 kW, while in the case of a 6 mm long cavity the maximum power is about 130 kW. Therefore, after that, a gyrotron with a 6 mm long cavity made of stainless steel with copper coating allowing for smaller ohmic losses was tested in more detail. The fact that the maximum efficiency was realized in a longer cavity indicates that in this experiment the electron pitch ratio was smaller than its design value of 1.27. To optimize the orbital-to-axial electron velocity ratio (beam pitch-factor) the position of cathode was slightly changed in the axial direction. These changes had allowed us to reach the maximum radiation power averaged over a single pulse equal to 210 kW. This power level was achieved with a 58 kV, 22 A electron beam and corresponds to 16.5 % output efficiency. The maximum output efficiency of 20 % was realized at lower currents, viz. in 57 kV, 16 A operating regime. Taking into account microwave losses in a 2 mm thick teflon window (17–20 %) and about 9–10 % of ohmic losses of the power radiated in the $TE_{31,8}$-mode one can conclude that the interaction efficiency in this experiment was at about 30 % level that agrees reasonably well with the simulation data. The radiated power was converted with the use of standard quasi-optical methods into a Gaussian-like wave beam and focused by a focusing mirror.

In summary, it has been experimentally demonstrated that with a gyrotron operating in pulsed magnetic field coherent 670 GHz radiation with the microwave power of 210 kW, 20 % efficiency and the microwave energy of 6.3 J in single shots were obtained [7].

Conclusions. Despite the requirement of strong operating magnetic fields, the THz frequency has been achieved by the pulse gyrotrons operating at the fundamental harmonic. Today it is clear that relatively small-size tubes with a high level of output power (from a hundred to several kilowatts) at the frequencies of 0.3–1.5 THz will be available soon for many applications.

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РОЗРОБКА Й ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ПОТУЖНИХ ІМПУЛЬСНИХ ГІРОТРОНІВ ТЕРАГЕРЦОВОГО ДІАПАЗОНУ

Терагерцове (ТГц) випромінювання привертає надзвичайну увагу для ініціації локалізованого газового розряду, дистанційного виявлення джерел іонізуючого випромінювання, діагностики плазми методами колективного томпсонівського розсіяння, створення спектроскопічних комплексів високого розрізнення, нових медичних технологій та ін. Для вирішення зазначених задач необхідні потужні та відносно компактні джерела ТГц-випромінювання. У статті описані потужні гіротрони, які створені в ІПФ РАН на базі імпульсних соленоїдів з інтенсивністю поля до 50 Тл, що дозволили реалізувати генерацію потужного мікрохвильового випромінювання на основному циклотронному резонансі, коли відносно просто вирішується проблема селекції робочого типу коливань. При тривалостях імпульсу 40 мкс на частоті 0,67 ТГц отримано потужність до 200 кВт, 5 кВт – на частоті 1 ТГц і 0,5 кВт – на частоті 1,3 ТГц. Незважаючи на складність створення магнітних полів високої інтенсивності, виконані роботи демонструють можливість створення в найближчому майбутньому широкодоступних джерел потужного імпульсного ТГц-випромінювання.

Ключові слова: ТГц-випромінювання, кВт-рівень потужності, гіротрон, імпульсний соленоїд.

М. Глявин, А. Лучинин, М. Морозкин

РАЗРАБОТКА И ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ МОЩНЫХ ИМПУЛЬСНЫХ ГИРОТРОНОВ ТЕРАГЕРЦЕВОГО ДИАПАЗОНА

Терагерцевое (ТГц) излучение представляется крайне привлекательным для инициации локализованного газового разряда, дистанционного обнаружения источников ионизирующего излучения, диагностики плазмы методами коллективного томпсоновского рассеяния, создания спектроскопических комплексов высокого разрешения, новых медицинских технологий и др. Для решения указанных задач необходимы мощные и относительно компактные источники ТГц-излучения. В статье описаны созданные в ИПФ РАН мощные гиротроны на базе импульсных соленоидов с интенсивностью поля до 50 Тл, позволившие реализовать генерацию мощного микроволнового излучения на основном циклотронном резонансе, когда относительно просто решается проблема селекции рабочего типа колебаний. При длительностях импульса 40 мкс частоте 0,67 ТГц получена мощность до 200 кВт, 5 кВт – на частоте 1 ТГц и 0,5 кВт – на частоте 1,3 ТГц. Несмотря на сложность создания магнитных полей высокой интенсивности, выполненные работы демонстрируют возможность создания в ближайшем будущем широкодоступных источников мощного импульсного ТГц-излучения.

Ключевые слова: ТГц-излучение, кВт-уровень мощности, гиротрон, импульсный соленоид.