Generation of kW level THz radiation by the gyrotron with pulsed magnetic field

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***Abstract*— To cover a so-called terahertz gap in available sources of coherent electromagnetic radiation, the gyrotron with a pulsed solenoid producing up to 50 T magnetic field has been designed, manufactured and tested. At 38.5 T magnetic field, the gyrotron generated coherent radiation at 1.022 THz frequency with pulse duration about 50 microseconds. 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. The highest for gyrotrons generation frequency 1.3 THz has been obtained at 48.7 T magnetic field.**

I. Introduction

GYROTRONS are known as devices capable of producing coherent powerful electromagnetic radiation at millimeter and submillimeter wavelengths. Development of compact, simple and reliable sources of coherent terahertz (THz) radiation is important for numerous applications, which include plasma diagnostics, electron-spin resonance spectroscopy, enhancement of NMR sensitivity using dynamic nuclear polarization, detection and imaging of explosives and weapons, new medical technology, atmospheric monitoring, production of high-purity materials, deep space and specialized satellite communication, etc. Today there are known solid-state and vacuum electron sources delivering THz radiation. Gyrotrons are much more compact than powerful free electron lasers because they do not require large accelerators or high-voltage modulators. On the other hand, the gyrotrons can realized essentially higher output power comparing with solid state devices.

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 the radiation frequency of 1 THz; at higher harmonics magnetic field decreases inversely proportional to the cyclotron harmonic number, but the problem of mode competition restrict the possibility of high harmonic operation. Typically, magnetic field, which can be produced in cryomagnets with a large enough inner bore, do not exceed 20 T. Higher magnetic fields can be realized with the use of pulsed magnets.

II. Experimental results

A demountable compact THz gyrotron tube (Fig.1) 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[1] and on the development of an improved pulsed solenoid[2].

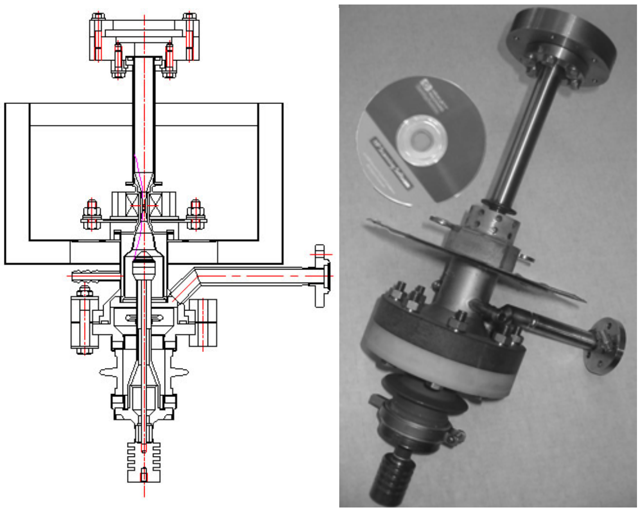

Fig.1. The pulsed magnet gyrotron general view

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 cyclotron resonance condition accurately enough, 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 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 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. 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%. Due to limitations caused by cooling the pulsed

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solenoid, the repetition rate was limited by one shot in a minute. After more than 2500 pulses with magnetic fields above 30T no signs of solenoid deterioration had been observed.

Gyrotron components included the conventional cylindrical cavity (3 mm diameter and 3mm 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 microseconds). The cavity was made of a special sort of 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.2.

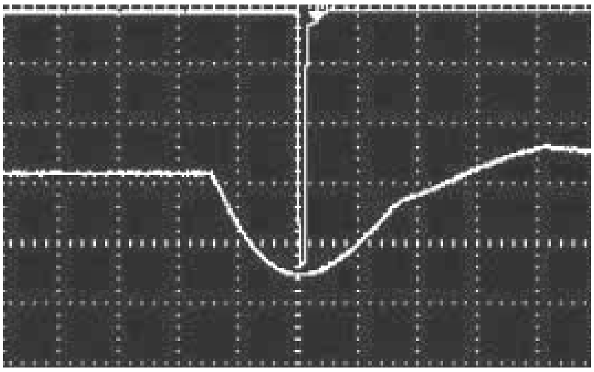

Fig.2. The high-voltage pulse (50 mcs) synchronized with the peak of the pulsed magnetic field (1 division is equal to 0.5 ms)

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 with sensitivity about 10 mJ in single shot. 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. At the magnetic field close to 38.5 T, the $TE_{17,4}$ mode was excited at 1.022 THz frequency[3]. The microwave pulse of this mode is shown in Fig.3.

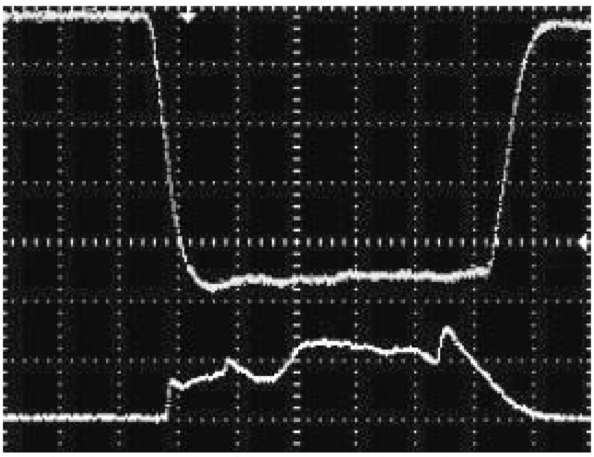

Fig.3. The microwave pulse of the $TE_{17,4}$ operating mode. Upper trace – high voltage pulse, lower trace – microwave signal from detector.

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 reason for a relatively low efficiency is the cavity length which is about two 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 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 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.

The maximum magnetic field about 50 T was achieved and the highest for gyrotrons generation frequency 1.3 THz has been obtained at 48.7 T magnetic field. The radiation power averaged over the pulse was about 0.5 kW. Due to cooling limitations, the repetition rate was reduced to one shot in five minutes. The experimental results are summarized in the Table.

Magnetic field, T	35.4	36.9	37.5	38.3	48.7
Oscillation frequency, THz	0.945	0.984	1.002	1.024	1.300
Microwave pulse energy, mJ	63	62	87	60	10
Pulse duration, mcs	40	50	40	40	20
Average power, kW	1.58	1.25	1.75	1.58	0.5
Operating mode	$TE_{15,4}$	$TE_{16,4}$	$TE_{6,8}$	$TE_{17,4}$	$TE_{24,4}$

So, in the experiment with gyrotron operating in pulsed magnetic field, coherent THz radiation with the kW microwave power level was obtained.

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