Development of a Tera Hertz Gyrotron as a Radiation Source

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The gyrotron FU-VI, which can oscillate in the terahertz region has been developed. Tera-hertz operations with the second harmonic operation have been detected by a hot electron detector after a high-pass filter and/or a band-pass filter. The main magnetic field coil of the FU-VI is a pulse magnet coil protected by ice with alumina powder, and can generate the magnetic field 20 T or higher in the resonant cavity. One of the second harmonic operations has been confirmed experimentally at 1.010 THz due to $TE_{4,12}$ cavity mode at the magnetic field 19.1 T in the resonator.

Keywords: gyrotron, radiation source, terahertz, middle power, pulse magnet coil

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1. Introduction

The development of Gyrotrons are being advanced in two ways. The major way is development of high power, millimeter wave gyrotrons for heating and current drive for fusion plasma. It is going on worldwide and has achieved around 1MW output power for long pulse operation (longer than several tens second or quasi CW) at the frequency of 170 GHz or 140 GHz [1]. On the other hand, medium power, high frequency gyrotrons are being developed in several institutions in the world. In these cases, high magnetic field and higher harmonic operations are used to increase the operation frequency. Such gyrotrons have already covered a wide frequency range from millimeter to submillimeter wavelength region and been applied as submillimeter wave radiation sources to wide fields including plasma diagnostics, electron spin resonance (ESR) spectroscopy [2], new medical technology and so on. These gyrotrons are the only stable high power THz radiation source and will be important and useful in the future for development of high power THz technologies.

Our gyrotrons named Gyrotron FU series, which have been developed in 'Research Center for Development of Far-Infrared Region, University of Fukui' (FIR FU), belong to the second type of gyrotrons, that is, medium power high frequency gyrotrons. The series has achieved following items [3], 1) frequency step-tuneability in wide range in millimeter to submillimeter wavelength region (from 38 to 889 GHz), 2) highest frequency (889 GHz) corresponding to the wavelength of 377 μm by using the second harmonic operation at the field intensity of around 17 T, 3) modulation of amplitude and frequency of the output, 4) stabilization of amplitude and frequency, 5) higher harmonic operations up to fifth and 6) high-purity mode operations at many cavity modes by installation of a carefully designed cavity. In addition, we have achieved mode conversion from circular waveguide modes to a Gaussian mode for applications of our gyrotrons to many fields.

However, up to the present, gyrotrons have not achieved the operation at the frequency of one terahertz. This paper presents that a THz gyrotron with a pulse magnet has been designed, constructed and operated in FIR FU. It is developed as one of the high frequency gyrotrons included in Gyrotron FU Series. The gyrotron has already achieved the first experimental result for high frequency operations whose radiation frequency exceeds 1 THz. In this presentation, the design detail and the operation test results for sub-terahertz to terahertz range are described. The second harmonic operation is confirmed experimentally at the expected frequency of 1.01 THz due to $TE_{4,12}$ cavity mode at the magnetic field intensity of 19.1 T.

2. Design of THz Gyrotron FU-VI

Figure 1 is a tera-hertz gyrotron FU-VI system developed in FIR FU. The gyrotron tube and the main magnet coil are cooled down by liquid nitrogen in the cryostat. A high-voltage power supply (Rated voltage: 40 kV, Rated current: 6 A, Maximum pulse length: 1 ms) and a heater power supply are connected to the triode type electron gun. A high-current power supply (Rated current: 0.5 kA) is connected to the gun coil. Controllers are set up in the next room, and isolated from the high voltage zone. A high-power supply which is a capacitor bank (Rated voltage: 10 kV, Capacitance: 6 mF) for the main magnet coil is set up downstairs.

Figure 2 is the draft of the tera-hertz gyrotron. The gyrotron has a main magnetic field coil and gun coils. The

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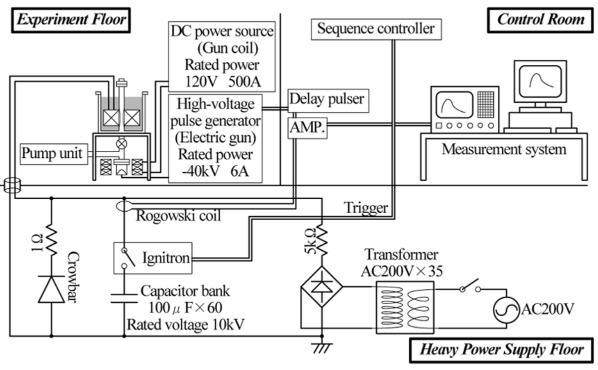

Fig. 1 Whole diagram of tera-hertz gyrotron system.

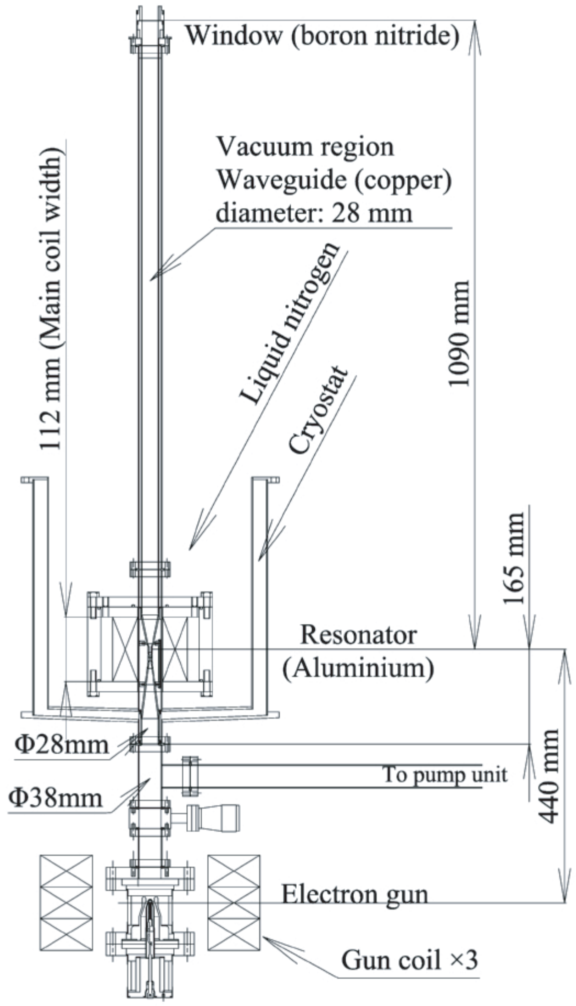

Fig. 2 The draft of tera-hertz gyrotron.

center of the main coil is set at the center of the cavity (resonator). The coil is submerged in a cryostat filled by the liquid nitrogen. The vacuum layer of the cryostat and the vacuum chamber are connected and pumped by one pump unit which consists of a rotary pump, a turbo molecular pump and an ion pump. The electron gun is surrounded by

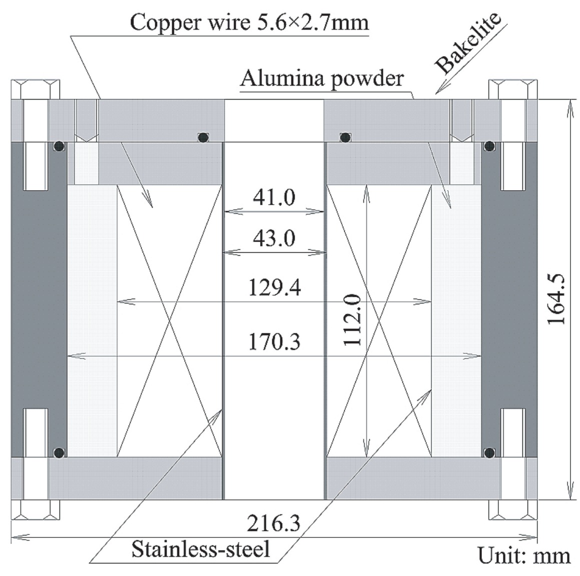

Fig. 3 Cross-section of the main coil. The coil is an ice-protecting type. The number of turns of the rectangular copper wire is about 300 (sixteen layer).

gun coils. The vertex of the vacuum gyrotron tube is sealed with the boron nitride (BN) window.

The magnetic field strength of about 20 T at the resonator region is necessary for the terahertz oscillation by the second harmonic operation with gyrotrons. Figure 3 is the cross-section of the THz gyrotron's main coil which can generate magnetic field strength of 20 T or more. The main magnetic field is generated in pulse. A stainless steel pipe of the center is the coil bobbin and is thinned in order to decrease the Eddy current. Two mechanisms cope with the Lorentz force between the coil current and its magnetic field. One is a tensile strength of the copper wire and the other is the strength of the outer stainless steel pipe (thickness: 23.0 mm). Between the copper wire and the outer stainless steel pipe, alumina powder containing water has been packed. The water of niche of the powder becomes ice with cool down by the liquid nitrogen. Inside the outer stainless steel pipe, its expansion pressure keeps pushing the copper wire inward and resists to the Lorentz force. The crack in the layer of the alumina powder and ice caused by the strong impulsive force based on the Lorentz force is repaired whenever it is refrozen. The alumina is an electrical insulant and promotes the heat radiation. The high-power supply (Rated voltage: 10 kV) is connected to the coil, so that the inside of the wire layer approaches the ground potential. The pulse interval of the THz gyrotron FU-VI is 30 minutes based on the cooling time of the coil.

Figure 4 is the cavity around the resonator of the THz gyrotron. The diameter and the length of the resonator are 3.9 mm and 10.0 mm, respectively. The cutoff waveguide of this cavity has the diameter of 3.0 mm and the length of 10.0 mm. In order to reduce the effect of the Eddy current,

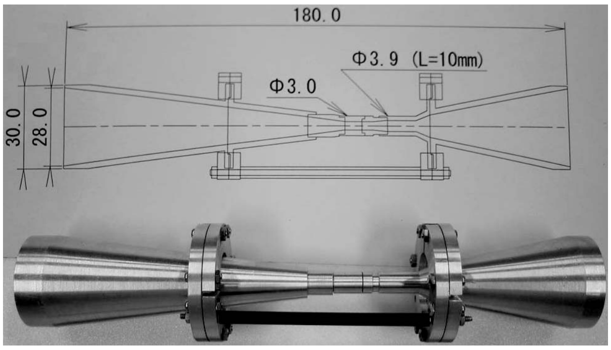

Fig. 4 The draft and the photograph of the cavity of the THz gyrotron. The diameter and the length of the resonator are 3.9 mm and 10.0 mm, respectively. All parts except the props are made of aluminum.

this cavity was made of aluminum, and the wall thickness was thinned (2 mm). Three props of the cavity resist the impulsive force of the Lorentz force between the pulsed magnetic field and the Eddy current by its pulsed magnetic field.

3. Experimental Setup

The tera-hertz oscillation is detected by the hot electron detector as shown in Fig. 5. The tera-hertz wave is transmitted from the resonator to the detector by circular waveguide and three miter bends. The distance from the resonator to the BN window is 1090 mm (vacuum region). The distance from the window to the high-pass filter is 3070 mm (air region). The filter is made of copper. The diameter and the length of the hole at the center are 0.3 mm and 2.1 mm, respectively. The inclination angle of the taper is 45 degrees. The cutoff frequency of this filter is 0.586 THz. We used a hot electron detector after a high-pass filter and/or a band-pass filter (metal mesh). The band-pass filter whose characteristic is shown in Fig. 6 is installed on the detector side.

4. Experimental Result

The gyrotron FU-VI achieved the 1 THz oscillation. Figure 7 is one of the results. Figure 7 (a) shows the electron beam voltage. In this case, the cathode voltage and pulse length was set at 30 kV and 1 ms, respectively. Figure 7 (b) shows the magnetic field in the resonator which was calculated from the coil current. The main coil generates the magnetic field 19.3 T at the 6.6 ms. The signal of Fig. 7 (c) was detected by the hot electron detector after the high-pass filter (diameter: 0.3 mm).

Figure 8 is the close-up of the oscillating time zone in Fig. 7. The output power was detected at 5.9 ms: the magnetic field at this time was 19.1 T. The magnetic field becomes 19.1 T again at 7.3 ms. However, in this case, there is no oscillation because the electron beam pulse ends at the 7.3 ms.

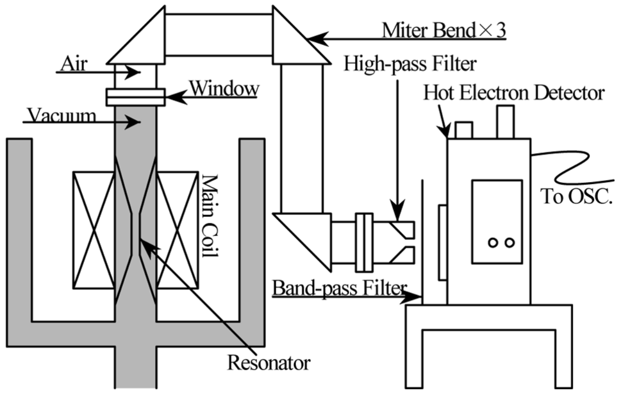

Fig. 5 Measurement system of tera-hertz oscillation. The output power of the tera-hertz wave is transmitted about 4 m by the three miter bends and the waveguide whose diameter is 28 mm. From the gyrotron window to the detector window is the atmospheric pressure. The tera-hertz wave power is detected by the hot electron detector after a high-pass filter and/or band-pass filter.

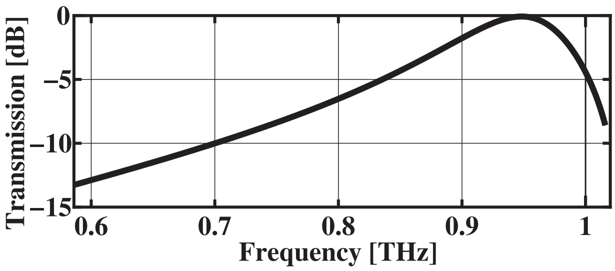

Fig. 6 Attenuation characteristic of band-pass filter.

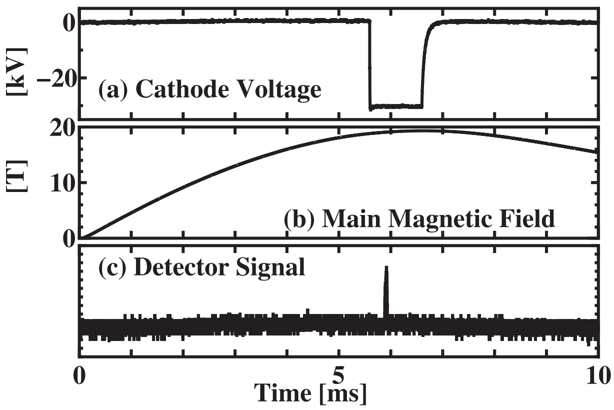

Fig. 7 Radiation power measured as a function of time by use of the hot electron detector.

In this experiment, the output is measured after the two filters. At magnetic field 19.1 T, the electron cyclotron frequency (beam energy: 30 kV) is 0.505 THz. The fundamental operation wave cannot pass the high-pass filter (cutoff frequency: 0.586 THz). Therefore, the frequency of the detected signal is 1.010 THz of the second harmonic

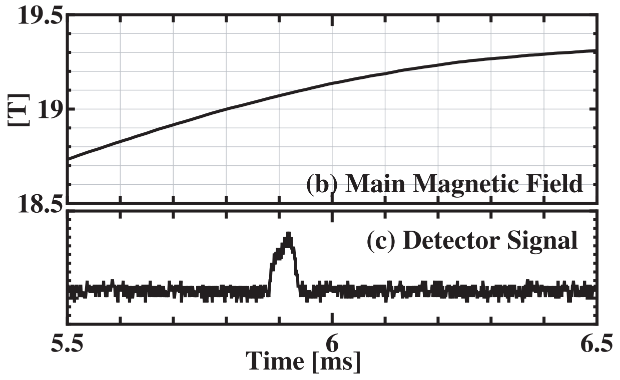

Fig. 8 Close-up of the oscillation time in Fig. 7.

operation. The signal whose frequency is higher than the second harmonic operation should cut by the band-pass filter.

5. Discussion and Conclusion

The gyrotron FU-VI achieved the 1 THz oscillation by the second harmonic operation with the main magnetic field 19.1 T. Judging from Fig. 9, the operation mode in Fig. 7 (c) is $TE_{4,12}$, because the magnetic field of oscillation is 19.1 T (second harmonic operation). Figure 9 shows the starting current of the waveguide mode at 19 T region where the fundamental and second electron cyclotron wave are about 0.5 and 1 THz, respectively. The magnetic field is calculated from the electron cyclotron frequency with the effect of the relativistic factor of the electron beam. The signal in Fig. 8 (c) does not contain the output power of the fundamental operation, because the high-pass filter has the cylinder length of 2.1 mm. The output power of the fundamental operation whose frequency and wave length are 0.5 THz and 0.6 mm, respectively, is surely cut with the high-pass filter (cutoff frequency: 0.586 THz).

Table 1 shows simulation data with the $TE_{4,12}$ mode. The simulation parameters of the electron beam are correspond to the experimental parameters. The gyrotron FU-VI might have obtained output power strong enough as a terahertz optical source. If the pulse width become longer, the gyrotron FU-IV will become a more valuable source.

The output power of Fig. 8 (c) is thought to be watt order, because our detector couldn't detect the output power of less than 10 W at 889 GHz oscillation [4]. However, it is necessary to measure the output power in order to use it as a terahertz radiation source. The sensitivity of the hot electron detector in 1 THz region is unclear. The output power cannot be measured by water load, because the pulse interval is too long. It is also necessary to examine the attenuation factor of the transmission line. The electromagnetic wave that exceeds the frequency 0.9 THz is attenuated strongly by the water molecule in atmosphere [5]. The decay-rate estimation of the high-pass filter has not been done yet.

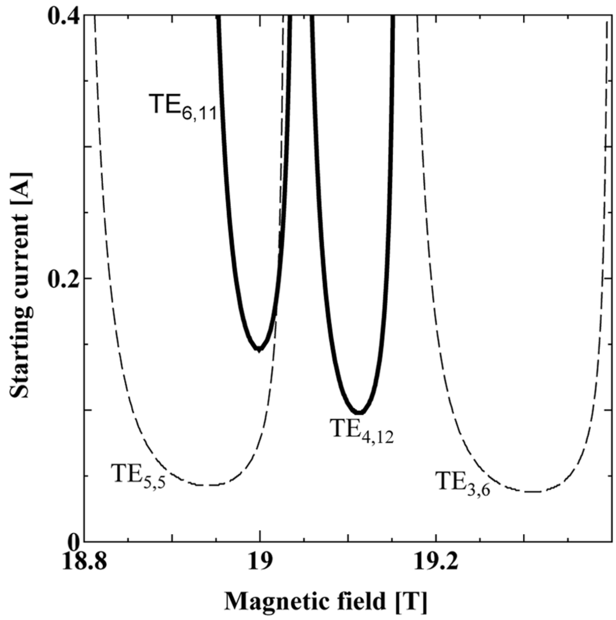

Fig. 9 Starting current with the beam energy 30 kV. The solid lines are the second harmonic line. (1 THz region) The dashed lines are the fundamental line.(0.5 THz region).

Table 1 Simulation data for the THz gyrotron FU-VI. The oscillation mode is $TE_{4,12}$ by second harmonic operation. The diameter of the resonator is 3.9 mm.

Oscillation frequency	1.010 THz
Output power	350 W
Efficiency	5.9%
Cathode voltage	30 kV
Beam current	200 mA

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