Development of THz gyrotrons and application to high power THz technologies

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Abstract: A gyrotron with a 21 T pulse magnet achieved the breakthrough of 1 THz. This is the first result of high frequency operation in the world beyond 1 THz. In addition, new gyrotron series in FIR FU, University of Fukui, so-called Gyrotron FU CW Series is being developed. Such a present status of high power THz radiation sources - gyrotrons in FIR FU and their application to high power THz technologies will be introduced.

Keywords: THz source, Gyrotron, High power THz technologies

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1. Introduction

Our previous Gyrotron FU Series has already achieved high frequency operation up to 0.89 THz by using a 17 T magnet and the second harmonic operation.1) Recently, a gyrotron in FIR FU with a 21 T pulse magnet achieved the breakthrough of 1 THz. 2) For convenience of the application to high power THz technologies, CW gyrotrons (Gyrotron FU CW Series) is being developed. Gyrotron FU CW I has been developed and succeeded in the CW operation at 300 GHz under high power of 1.75 kW.3) The next gyrotrons, Gyrotrons FU CW II and III are being developed. The parameters are as follows, 394 GHz, 100 W for FU CW II and 1 THz 100 W for FU CW III. Both gyrotrons operate in CW mode.

2. A THz gyrotron with a pulse magnet

A demountable gyrotron tube is installed on the center axis of 21 T pulse magnet. In the operation test, a high voltage pulse is applied to electron gun at around the maximum field intensity B. When B is changed, many cavity modes are excited at the fundamental and second harmonic of cyclotron frequency. Fig. 1 shows expected frequency of observed radiation as functions of B. The second harmonic radiation is separated from the fundamental by using a high pass filter. The maximum frequency is around 1.016 THz at the second harmonic operation of $TE_{4,12}$ cavity mode.

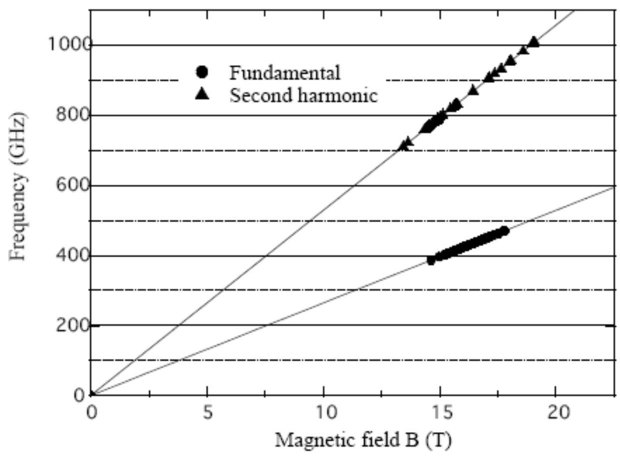

Fig.1 Expected frequencies as function of magnetic field intensity B.

Corresponding field intensity B is 19.1 T. Now we are trying to increase the frequency by increasing B. Similar study on development of a high frequency gyrotron with a pulse magnet is advancing in Institute of Applied Physics, Russian Academy of Science (IAP-RAS).4)

3. Gyrotron FU CW Series

In FIR FU, we are developing high frequency CW gyrotrons named Gyrotron FU CW Series as high power THz radiation source. We have already developed Gyrotron FU CW I. The frequency is 300 GHz, output power 1.75 kW, the operation is complete CW.3)

3.1. Gyrotron FU CW II

Just, we have finished the construction of a next CW gyrotron, Gyrotron FU CW II and begun the operation test. Fig. 2 shows a cross section of the gyrotron and Fig. 3 the side view. The gyrotron consists of a 12 T He-free superconducting magnet, a demountable tube, a vacuum pump system and power supplies. The cavity is a simple cylindrical one whose diameter and length are 5.72 mm and 15 mm. The designed frequency is 394.6 GHz at the second harmonic operation of TE2,6 cavity mode. After completing the operation test, the gyrotron will be used for enhancement of NMR sensitivity by use of dynamic nuclear polarization (DNP). 394.6 GHz is corresponding to ESR frequency at the field intensity of 7.1 T. The frequency of proton NMR at the field is 600 MHz.

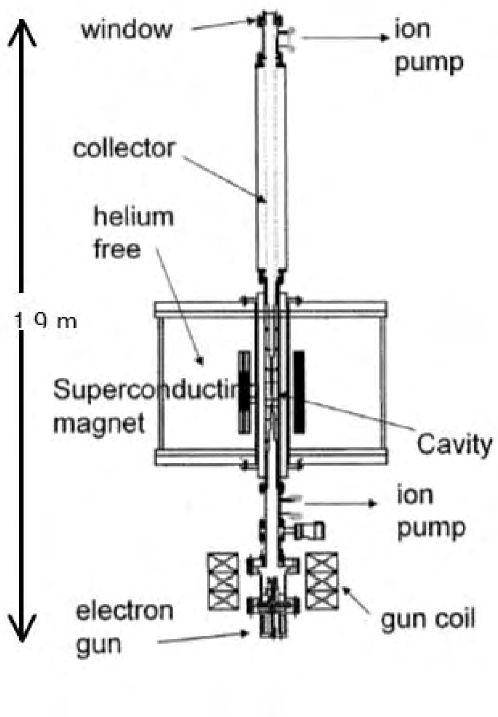

Fig. 2 The cross section of Gyrotron FU CW II

Fig. 3 Sideview of Gyrotron FU CW II

We have already succeeded to operate the gyrotron at many fundamental and second harmonic resonances. Cavity modes corresponding almost all radiations resulting from fundamental and second harmonic operations are identified. We have found the operation at the $TE_{0,6}$ cavity mode whose frequency measured by a heterodyn system is 394.3 GHz. It is a little bit lower frequency than the designed frequency. Fig. 4 shows all of frequencies observed up to the present as functions of magnetic field intensity. Measured frequencies are distributed in the range from 61GHz to 209 GHz in the case of fundamental operations, while from 212 to 439 GHz in case of second harmonic operations. Now, we are measuring the output power of Gyrotron FU CW II. Typically, the output power is several hundred watt for fundamental operations and several tens watt for the second harmonic operations.

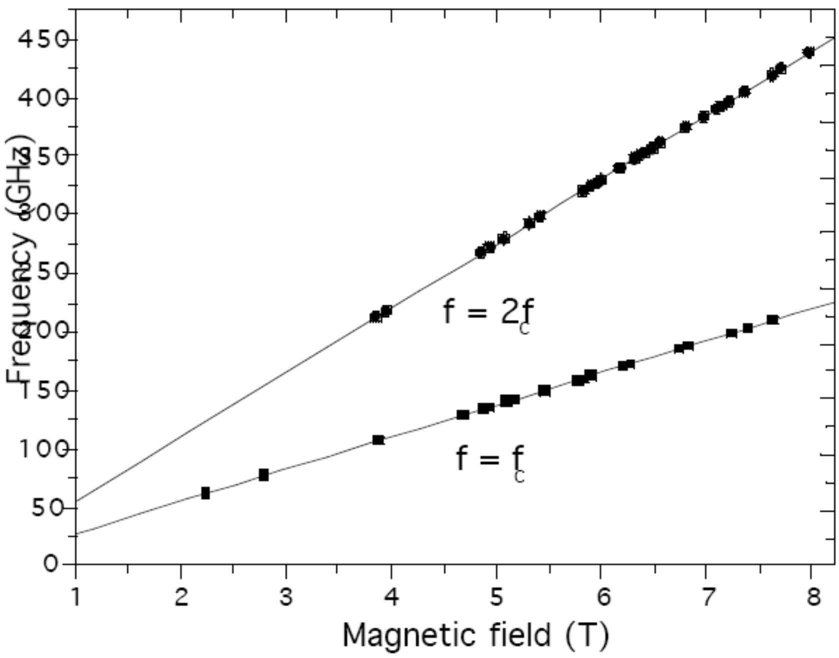

Fig. 4 All frequencies measured by a heterodyn detection system as functions of magnetic field

3.2. Gyrotron FU CW III

The third gyrotron, Gyrotron FU CW III with a 20 T superconducting magnet 5) has already been constructed and will be operated soon. In Table 1, main parameters of the gyrotron are shown. The gyrotron is optimized for the second harmonic operation of $TE_{4,12}$ at the frequency of 1013.7 GHz. The operation mode is complete CW. This gyrotron will achieve the breakthrough of 1 THz in CW operation. In addition, it is expected that many other cavity modes will be excited by adjusting the field intensity at the optimum value for each cavity mode. As the results, it will achieved frequency step tenability in wide range covering sub-THz to THz frequency region.

Fig. 5 and Fig. 6 show the cross section and a photo of Gyrotron FU CW III. Figure 7 shows measurement results of radiation power at fundamental operations and calculation results for starting currents of each cavity modes at both fundamental (dotted lines) and second harmonic (solid lines) operations. It is seen that almost all cavity modes at the fundamentals are excited at the optimum intensities of magnetic field.

For measurement of the second harmonic operations, we tried to observe a radiation power after high pass filter consisting of a narrow circular wave guide whose diameter is 0.3 mm. The corresponding cutoff frequency is 586 GHz. Up to the present, we have measured several second harmonic operation in the field intensity region below 18 T. The maximum frequency estimated from the corresponding field intensity is around 980 GHz. Fig. 8 shows all of frequencies observed at both fundamental and second harmonic operations as function of field intensity at the cavity region. As seen in the figure, Gyrotron FU CW III has achieved frequency step-tunability in a wide region from 140 GHz to 980 GHz. Output power is distributed from around 100 W to higherthan 200 W at the fundamental operations and in several tens watt at the second harmonic operations. The operation mode is CW or long pulse with several hundred millisecond.

Total height from electron gun to the window: 2.4 m
Superconducting magnet : Maximum magnetic field : 20 T Inner bore : 50 mm
Cavity :Radius: 1.95 mm, Length : 10 mm,
Frequency : 1013.7 GHz at the second harmonic,
Main cavity mode : $TE_{4,12}$, Q-factor : 23720
Operation mode: Complete CW
Operating magnetic field: 19.1 T for: $TE_{4,12}$
Triode-type electron gun: Cathode radius: 4.5 mm, Maximum cathode current: 1 A, Cathode voltage: 30 kV
Gun coil: Maximum input current: 300 A, Maximum magnetic field: 0.183 T
Pumping bores: 1.Near the electron gun, 2.Near the output window.
Water cooling jackets are installed at a cavity and a collector regions.

Table 1 Specification of Gyrotron FU CW III

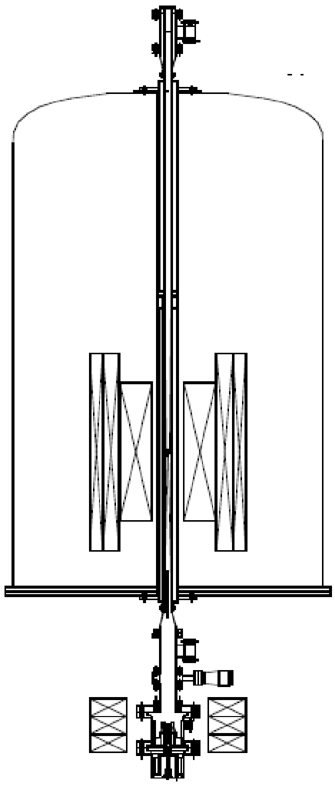

Fig. 5 The cross section of Gyrotron FU CW III

Fig.6 Photo of Gyrotron FU CW III

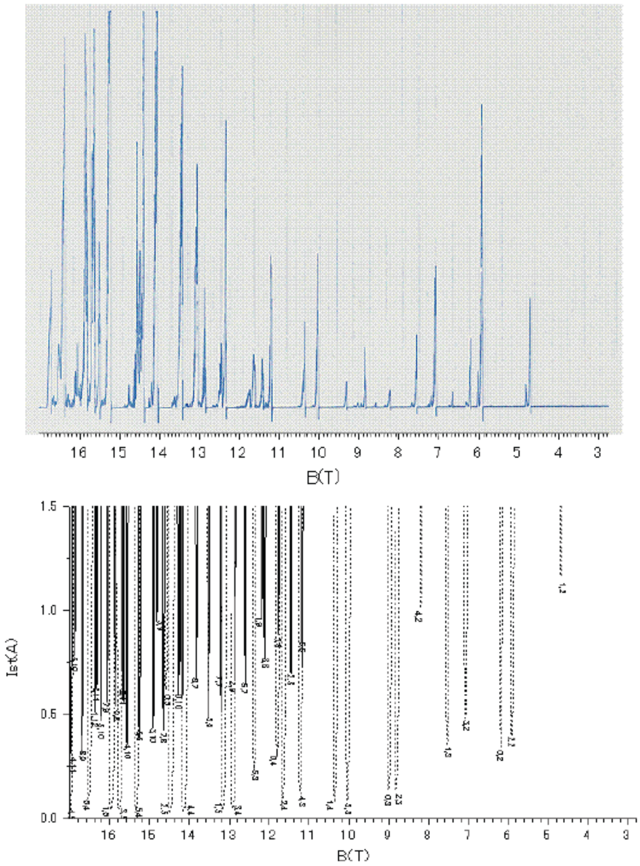

Fig. 7 A typical measurement result at the fundamental operations and comparison with calculation result for starting current of each cavity mode. Upper figure: Radiation power observed just after the output window as function of magnetic field intensity at the cavity region. Lower figure: Starting current for each cavity mode as a function of magnetic field intensity. Dotted lines show fundamental operations and solid lines second harmonic operations. Numbers indicated near calculated lines show mode numbers m, n. Comparing with the upper figure, it is seen that almost all cavity modes are excited at the optimum intensities of magnetic field for fundamental operations.

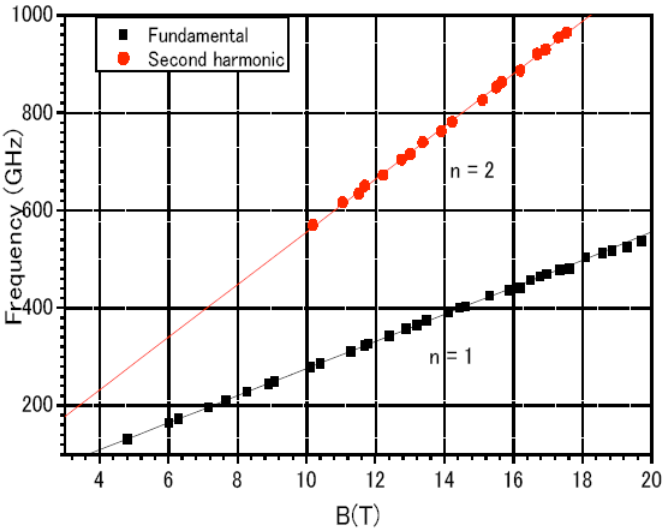

Fig. 8 All of frequencies observed at both fundamental and second harmonic operations.

4. Summary

Three CW gyrotrons, Gyrotron FU CW I, II and III operating in sub-THz to THz region are being developed. Operation test of FU CW I and II have already carried out. Gyrotron FU CW I is being used for material processing. Gyrotron FU CW II has been installed on a 600 MHz proton-NMR device at Institute of Protein Research, Osaka University for sensitivity enhancement of NMR spectroscopy by using Dynamic Nuclear Polarization (DNP). Gyrotron FU CW III will be used for development of high power THz technologies in future, after operation test is completed. These three gyrptrons have the advantages of complete CW operation and frequency step-tuneability in addition to high frequency operation up to 1 THz.

Now, we are developing the fourth gyrotron of the series, Gyrotron FU CW IV with 10T superconducting magnet. It will achieve continuously frequency-tuneability for application to DNP-NMR.

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