Development of high-harmonic gyrotrons using a permanent magnet system

Development of High-Harmonic Gyrotrons Using a Permanent Magnet System

TOSHITAKA IDEHARA,[1] ISAMU OGAWA,[2] KEN OHASHI,[3] and YOSUKE IWATA[1]
[1]Research Center for Development of Far-Infrared Region, Fukui University, Japan
[2]Cryogenic Laboratory, Fukui University, Japan
[3]Magnetic Material R&D Center, Shinetsu Chemical Co., Ltd., Japan

SUMMARY

A large-orbit gyrotron (LOG) operating at higher harmonics of the electron cyclotron frequency has been constructed by use of a permanent magnet system whose intensity is around 1 T. Operation tests have already been performed successfully up to the fourth harmonic. The operation efficiency is extremely high even at the third and fourth harmonics, because of highly efficient interaction between beam electrons and the high-frequency electric field in the LOG. The test results of the LOG are summarized.

Key words: gyrotron; LOG; permanent magnet; high-harmonic operation.

1. Introduction

Gyrotron development is advancing toward higher frequencies and higher powers. The frequency of a gyrotron is proportional to the intensity of the magnetic field, because the operation results from the "cyclotron resonance maser" mechanism. Therefore, we need the high magnetic fields which superconducting magnets produce [1] in order to achieve high-frequency operation. In this case, the treatment of the whole system is somewhat complicated because of the necessity of cryogenic devices, such as cryostats and transfer tubes for liquid helium.

As described in this paper, if a permanent magnet is used, the treatment of the system is much simpler and much more compact [2]. The intensity of the magnetic field generated by permanent magnet is 1 T. To achieve high-frequency generation in such a low field intensity, we need high-harmonic operation. Up to the present, high-harmonic operation has been used in a few gyrotrons [3]. In almost all cases, the second harmonic is used, and third-harmonic operation is difficult in conventional gyrotrons.

The main reasons for the difficulty are mode competition [4] between the fundamental mode and higher harmonic mode, and the lower efficiency of higher-harmonic operation. In the large-orbit gyrotron (LOG), such problems are solved, so that highly efficient operation is achieved at higher harmonics and pure single-mode operation is possible without mode competition [5, 6].

In this paper, development of the LOG, which has excellent advantages over conventional gyrotrons, and the results of operational tests of the LOG are described.

2. Operation Mechanism of LOG and Its Advantages

The LOG is characterized by its own special electron beam trajectory. In LOGs, a large-orbit electron beam whose guiding center is located at the center axis of the cavity is used [7], while in conventional gyrotrons, the guiding center is located at $r = R$ in the cavity. When we use such a large-orbit electron beam, the interaction with the TE_{mnl} cavity mode at the s-th harmonic resonance is efficient if $s = m$. This means that interactions with other cavity modes with $s \neq m$ do not occur and such modes are never excited. Therefore, the LOG operates in a single mode without mode competition. As a result, the LOG has the advantage of good mode selection.

When an LOG operates with the TE_{mnl} cavity mode, a beam electron is exposed to m cycles of high-frequency fields during one period of its cyclotron motion. If the harmonic number s is equal to the mode number m ($s = m$), the gyration motion of the beam electrons is synchronized with the TE_{mnl} cavity mode and high-efficiency operation is possible even at high harmonics because of highly efficient energy transfer from the beam electrons to the electromagnetic wave. This advantage allows the LOG to operate easily at high harmonics.

Up to the present, large-orbit electron beams have been generated by a cusp magnetic field. In this case, the deviation of the guiding center from the center axis is not small, and as a result the energy transfer efficiency from beam electrons to electromagnetic waves is decreased and the output power is also decreased.

As an alternative device, we tried to produce an axis-encircling large-orbit electron beam by using a gradually increasing field profile for development of highly efficient, high-harmonic gyrotrons. Finally, we succeeded in generating an electron beam with small deviation of the guiding center by using a 1-T permanent magnet and a new specially designed electron gun. Thus, we can achieve third- and fourth-harmonic operations with an output power of several kilowatts using a fairly low-energy electron beam with V_b equal to about 40 keV.

3. Experimental Apparatus and Procedures

Figure 1 shows the cross section of the LOG. It consists of a magnet system including a permanent magnet and a gyrotron tube including an electron gun, a resonant cavity, and an output window.

3.1 The magnet system

The magnet system of the LOG consists of many elements made from Nd, Fe, and B. Figure 2 shows the cross section of the magnet circuit and Fig. 3 the field distribution in the z direction on the center axis. The region limited by two broken lines (about 50 mm in length) indicates the resonant cavity region; a uniform magnetic field is applied there. The variation of the field intensity in the region is less than 3.9%. For fine adjustment of the field intensity, two additional coils are installed in the regions of the cathode and cavity. A coil in the cathode region has 10 layers, each

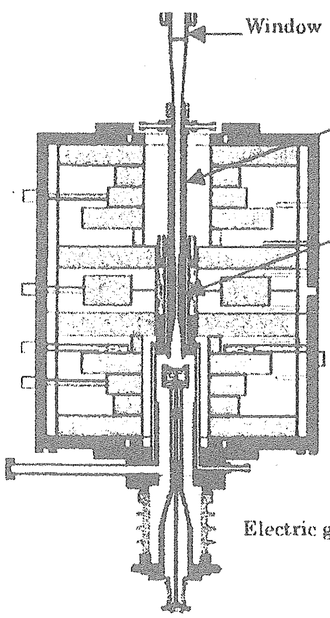

Fig. 1. Schematic drawing of LOG device.

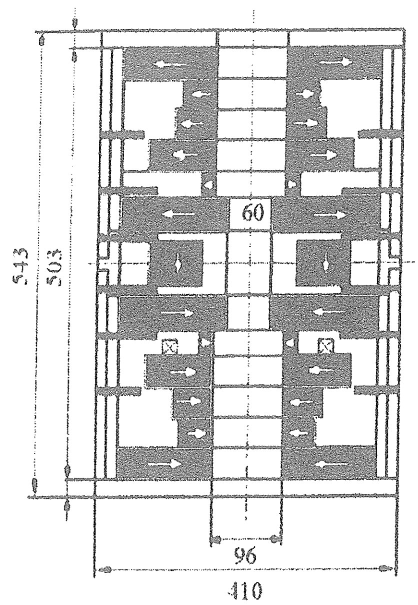

Fig. 2. Structure of a permanent magnet (magnetization of each element). The size is indicated in millimeters.

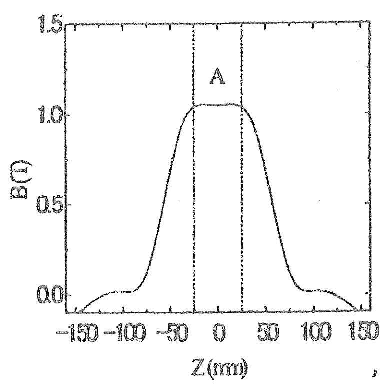

Fig. 3. Distribution of magnetic field of LOG magnet.

of which consists of 10 turns. The coil current can be increased to ±15 A and the rate of change of the field intensity is about 7 gauss/A. The coil in the cavity region has seven layers, each of which consists of 74 turns, and the rate of change of the field intensity is about 69.8 gauss/A. The coil current can be increased to ±20 A.

3.2 The gyrotron tube

Figure 4 shows a cross section of the gyrotron tube. In the region of the electron gun, electrons emitted from the circular emitting area are accelerated by the potential difference between the cathode and a body and a hollow electron beam is formed. This is a diode-type electron gun. The electrode surrounding the cathode directs the electric field inward and the beam electrons follow the electric field, because the magnetic field intensity is almost zero in this region. It gradually increases with the beam electrons passing through in the z direction. The electrons begin an axis-encircling gyration motion under the influence of the magnetic field. This situation is quite different from conventional gyrotrons, where the guiding center of a beam electron is located on a well-defined circle $r = R$ [8]. Gyrating beam electrons leave an electron gun, follow the lines of force, and enter the resonant cavity. In the case of s-th harmonic operation, the radius of the cavity should be

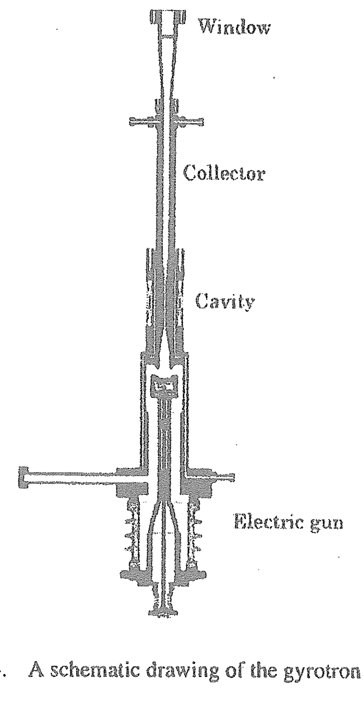

Fig. 4. A schematic drawing of the gyrotron tube.

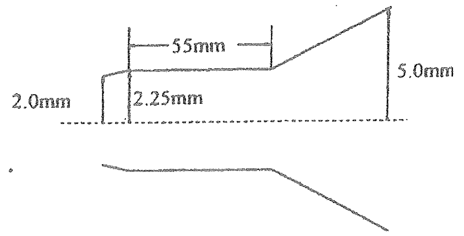

Fig. 5. A shape of a cylindrical cavity.

designed so that the resonant frequency of the TE_{sn1} mode is equal to s times of the electron cyclotron frequency.

Figure 5 shows a cross section of the resonant cavity in the gyrotron tube illustrated in Fig. 4. The design of this cavity is optimized for fourth-harmonic operation. The gyrotron tube is pumped out and high vacuum ($p \cong 10^{-7}$ Torr) is maintained inside the tube. The electromagnetic waves generated in the cavity are emitted from the output window. Therefore, we need to use low-loss material for the window. In this gyrotron, the window is made of boron nitride (BN).

3.3 Measurement procedures

The roughly estimated output power of this gyrotron is several kilowatts. The operation is in pulse mode with a duty ratio of 1/1000. We used a pyroelectric detector for the detection of electromagnetic waves. For measurement of the absolute value of the output power, we used a water load. In this case, we could measure the output power from the temperature increase of the water due to the absorption of the electromagnetic waves. For monitoring the real power absorbed by the water, a 1-W electrical heat source was installed and the temperature increase was compared with the case of electromagnetic wave absorption. For measurement of operating frequency, a frequency meter with a cylindrical cavity and a Fabry–Perot interferometer were used.

4. Experimental Results

4.1 Fourth-harmonic operation

As described already, fourth-harmonic operation occurs in the TE_{411} mode. In the cavity shown in Fig. 5, our simulation results for efficiency indicate operation near a field intensity of 1.07 T [8]. (See Fig. 6.) On the basis of the simulation results, we performed a test of fourth-harmonic operation. Figure 7 shows typical observed operating waveforms. It is seen that stable operation occurs during

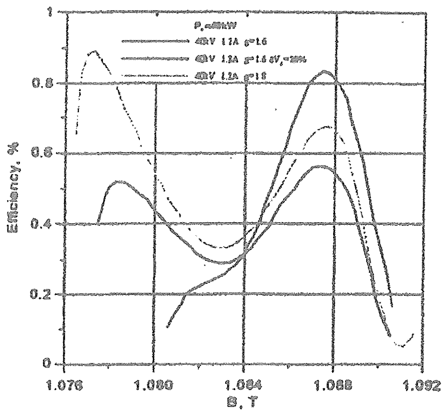

Fig. 6. Calculated results for operation efficiency.

a 1-ms pulse. Measurement of the output power was performed with the water load. The temperature increase was 0.08 °C per minute and the corresponding output power was estimated as 0.47 kW.

The frequency measured using a frequency meter with a cylindrical cavity was 112.696 GHz. The variation of the output power was measured while varying several parameters. In Figs. 8 and 9, the output power is plotted as a function of the acceleration voltage V and the field intensity B. The upper horizontal axis represents the corresponding cyclotron frequency f_c.

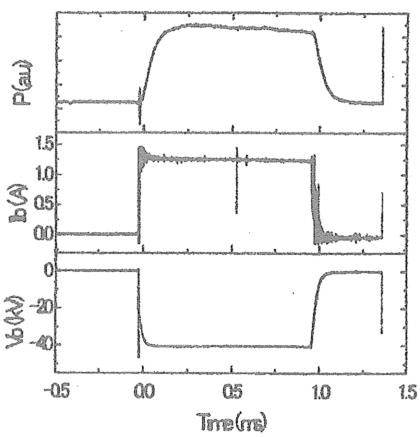

Fig. 7. Output power (P) with cathode voltage (V_b) and beam current (I_b).

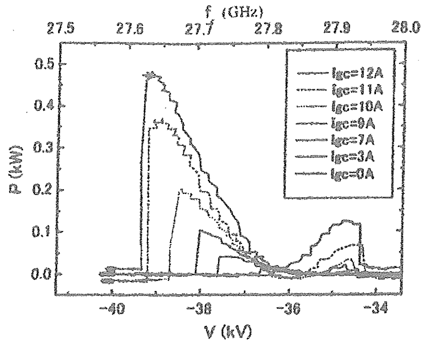

Fig. 8. Output power as a function of cyclotron frequency (acceleration voltage is varied).

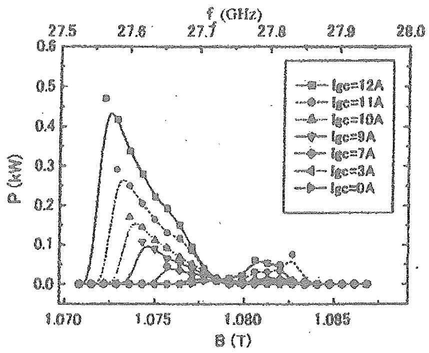

Fig. 9. Output power as a function of cyclotron frequency (field intensity is varied, $V_b = -40$ kV, $I_b = 1.3$ A).

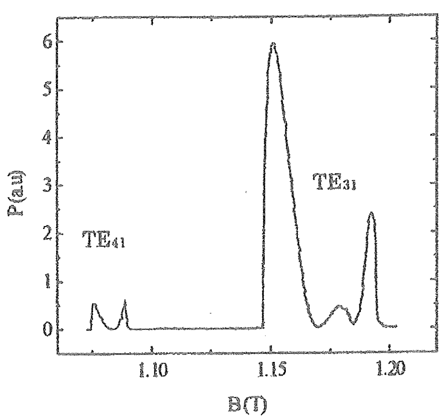

Fig. 10. Output power as a function of magnetic field intensity.

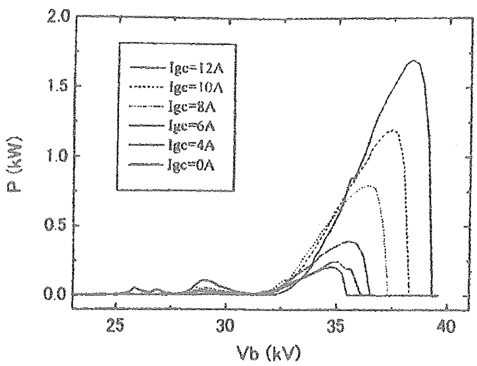

Fig. 11. Output power as a function of cathode voltage (fourth-harmonic operation).

4.2 Third-harmonic operation

This gyrotron can be operated at other harmonics if the field intensity is adjusted by an additional coil installed in the cavity region. We attempted third-harmonic operation, where a higher output power is expected. In Fig. 10, the measured output power is plotted as a function of the magnetic field B, while B is increased from the value for the fourth-harmonic operation. In the region of higher field intensity, three peaks with higher output power are observed. The corresponding frequency was 89.3 GHz. These results indicate operation at the third harmonic with TE_{31} cavity modes. As shown in Fig. 11, we sought the optimum condition for third-harmonic operation by varying the field intensities in the cavity region (B) and the gun region (the current of additional coil in the gun region I_{gc}). The maximum output power measured to date is 1.7 kW.

5. Summary

This paper describes the possibility of higher-harmonic operation in an LOG using a permanent magnet. In operating tests, a fourth harmonic at a frequency of 112.7 GHz and a third harmonic at 89.3 GHz were achieved. The corresponding output power and efficiency were 0.5 kW and 0.96% for the fourth harmonic and 1.7 kW and 3.3% for the third. A typical beam energy is 40 keV. This relatively high efficiency is obtained in high-harmonic operation by a rather low beam electron energy.

In the future, we will attempt higher-harmonic operation with longer pulses and also the application of LOG to various objectives.

Acknowledgments

This work was partially supported by a Grant in Aid from the Japanese Society for the Promotion of Science. It was carried out with the kind cooperation of two visiting professors at the Research Center for Development of Far-Infrared Region, Fukui University—Professor M. Glyavin of the Institute of Applied Physics, Russian Academy of Sciences, and Professor S. P. Sabchevski of the Institute of Electronics, Bulgarian Academy of Sciences.

REFERENCES

1. Idehara T, Tatsukawa T, Matsumoto S, Kunieda K, Hemmi K, Kanemaki T. Phys Lett A 1988;132:43.
2. Kikunaga T, Asano H, Yasojima Y, Sato F, Tsukamoto T. Int J Electron 1995;79:655.
3. Idehara T, Tatsukawa T, Ogawa I, Tanabe H, Mori T, Wada S, Kanemaki T. Appl Phys Lett 1990;5:1743.
4. Idehara T, Tatsukawa T, Ogawa I, Tanabe H, Mori T, Wada S, Brand GF, Brennan MH. Phys Fluids 1992;B4:267.
5. Glyavin M, Sabchevski S, Idehara T, Ogawa I, Mitsudo S, Ohashi K, Kobayashi H. Int J Infrared Millimeter Waves 2000;21:1211.
6. Sabchevski S, Idehara T, Ogawa I, Glyavin M, Ohashi K. Int J Infrared Millimeter Waves 2002;23:675.
7. Sabchevski S, Idehara T, Ogawa I, Glyavin M, Mitsudo S, Ohashi K, Kobayashi K. Int J Infrared Millimeter Waves 2000;21:1191.
8. Zapevalov V, Idehara T, Sabchevski S, Ohashi K, Manuilov V, Glyavin M, Kornishin S, Kuftin A, Lygin V, Malygin O, Moiseev M, Pavel'ev A, Tzalolikhin V, Zavolsky N, Kobayashi H, Yokoyama T, Ogawa I, Mitsudo S, Kanemaki T, Iwata Y, Hoshizuki H. Int J Infrared Millimeter Waves 2003;24:253–260.

AUTHORS (from left to right)

Toshitaka Idehara (member) B.S. 1963 Kyoto Univ., M.S. 1965 Kyoto Univ., D.Sc. 1968 Kyoto Univ., lecturer 1968 Fukui Univ., associate professor 1970 Fukui Univ., professor 1990 Fukui Univ., professor and director 1999 Research Center for Development of Far-Infrared Region, Fukui Univ. Research interests: development of high-frequency gyrotrons and applications to far-infrared technologies. Membership: Phys. Soc. Jpn., Jpn. Soc. Appl. Phys., Jpn. Soc. Plasma Sci. Nucl. Fusion Res., IEE Jpn., Jpn. Soc. Infrared Sci. Tech., Spectrosc. Soc. Jpn., High Temp. Soc. Jpn., Am. Phys. Soc.(APS)

Isamu Ogawa (nonmember) B.S. 1979 Ehime Univ., M.S. 1981 Nagoya Univ., D.Sc. 1991 Nagoya Univ., research assistant 1989 Fukui Univ., associate professor 1991 Fukui Univ., professor 2004 Research Center for Development of Far-Infrared Region, Fukui Univ. Research interests: development of high-power far-infrared wave sources and applications to plasma diagnostics. Membership: Phys. Soc. Jpn., Jpn. Soc. Appl. Phys., Jpn. Soc. Plasma Sci. Nucl. Fusion Res., Jpn. Soc. Infrared Sci. Tech.

Ken Ohashi (member) B.S. 1976 Tohoku Univ., M.S. 1978 Tohoku Univ., 1978 Shin-Etsu Chemical Co. Ltd., D.Eng. 1991 Tohoku Univ. Research interests: development of rare-earth permanent magnets and their applications. Membership: Phys. Soc. Jpn., Jpn. Soc. Appl. Phys., IEE Jpn., Jpn. Inst. Metals.

Yosuke Iwata (nonmember) B.E. 2001 Fukui Univ., M.E. 2003 Fukui Univ. Research interests: development of high-frequency gyrotrons. Membership: Phys. Soc. Jpn.