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A High Harmonic Gyrotron With an Axis-Encircling Electron Beam and a Permanent Magnet

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***Abstract*—A gyrotron with an axis-encircling electron beam is capable of high-frequency operation, because the high-beam efficiency is kept even at high harmonics of the electron cyclotron frequency. We have designed and constructed such a gyrotron with a permanent magnet. The gyrotron has already operated successfully at the third, fourth, and fifth harmonics. The frequencies are 89.3, 112.7, and 138 GHz, respectively, and the corresponding cavity modes are TE_{311}, TE_{411}, and TE_{511}. The permanent magnet system is quite novel and consists of many magnet elements made of NbFeB and additional coils for controlling the field intensities in the cavity and electron gun regions. The magnetic field in the cavity region can be varied from 0.97 to 1.18 T. At the magnetic field intensities, the output powers at the third and the fourth harmonics are 1.7 and 0.5 kW, respectively. The gyrotron is pulsed, the pulse length is 1 ms and the repetition frequency is 1 Hz. The beam energy is 40 kV and the beam current is 1.2–1.3 A. Beam efficiencies and emission patterns have also been measured. In this paper, the experimental results of the gyrotron are described and compared with computer simulations.**

***Index Terms*—Axis-encircling electron beam, gyrotron, high harmonic, permanent magnet.**

I. INTRODUCTION

THE development of gyrotrons is being advanced in two ways. One is the development of high-power, millimeter-wave gyrotrons. At the present time, a gyrotron with a diamond window has achieved 2 MW output power at 170 GHz in a pulse several seconds long [1]. Such high-power gyrotrons are being used for the electron cyclotron heating of fusion plasmas. The other is the development of high-frequency, medium-power gyrotrons as millimeter-to-submillimeter-wave radiation sources for a broad range of applications.

Our gyrotrons developed in the Research Center for Development of Far-Infrared Region at Fukui University (FIR FU) belong to the second type. In FIR FU, we have developed the Gyrotron FU Series which consists of nine gyrotrons. The gyrotron series has achieved frequency tunability over a wide range (from 38 to 889 GHz). With output powers rangins from several tens of watts to several tens of kilowatts. The highest frequency corresponds to a wavelength of 337 μm. This is a current record for high-frequency operation of gyrotron [2].

In order to develop such high-frequency gyrotrons, we usually require high magnetic fields generated by superconducting magnets [3] and/or operation at high harmonics of the electron cyclotron frequency [4], [5]. For FU IVA, for example, [6] a 17 T superconducting magnet is used. Operation with a superconducting magnet is complicated, because we need to transfer liquid helium from a container to cryostat, recover the evaporated helium, and liquefy it and so on.

Recently, we have developed a high harmonic gyrotron with an axis-encircling electron beam and a permanent magnet instead of a superconducting magnet. Operation is much simplified [7], but the field intensity is quite low compared with a superconducting magnet. It is only around 1 T. We have to use higher harmonic operation in order to obtain high frequencies. A gyrotron with an axis-encircling electron beam [a so-called large orbit gyrotron (LOG)] is capable of nth harmonic operation, employing the TE_{n11} cavity mode. In this case, the frequency of electromagnetic wave f is equal to n times the electron cyclotron frequency f_c and the axis-encircling electron beam feels n cycles of alternating electric field during one the electron gyration, and the interaction between an electron and electromagnetic wave is optimized and highly efficient operation is expected. In addition, the mode competition is minimal, because only the TE_{n11} cavity mode is excited when $f = nf_c$ [8].

In the case of the conventional gyrotron, higher harmonic operation is difficult to realize. The Gyrotron FU Series easily achieved second harmonic operations but third harmonic operation was very rare [9]. Efficiency decreases with harmonic number. On the other hand, in the case of LOG, higher harmonic operation (n =3, 4, 5) is easily excited [10], [11].

In this paper, the design of a LOG with a permanent magnet, construction and the results of preliminary tests are described.

II. OPERATION MECHANISM AND ADVANTAGES OF LOG

The LOG is characterized by the trajectory of the electron beam in the cavity it is known as an "axis-encircling electron

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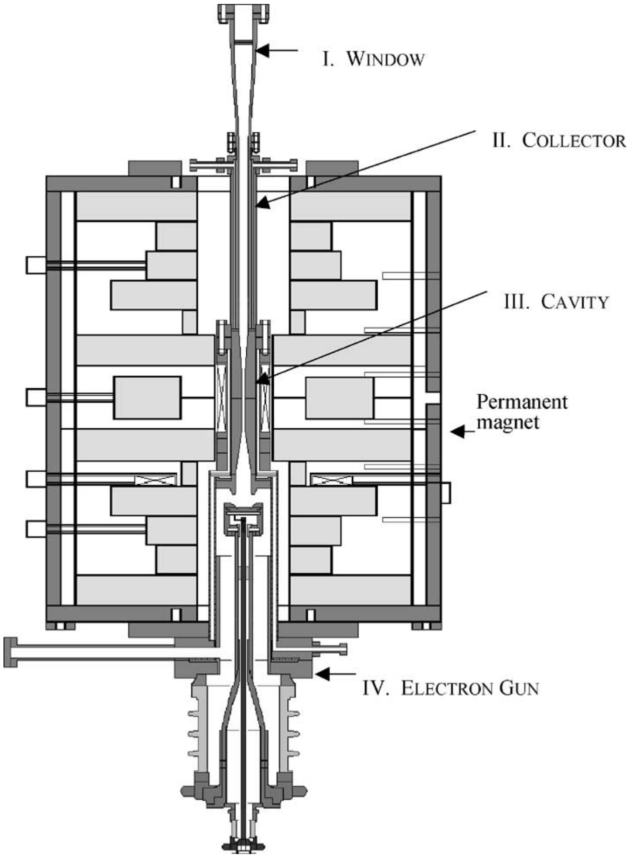

Fig. 1. Schematic drawing of the LOG device.

beam.” A beam electron gyrates around the center axis of the cavity [12], while in a conventional gyrotron, a beam electron rotates around a gyration center located on a concentric cylinder of the cavity. When we use an axis-encircling electron beam and the $\mathrm{TE}_{\mathrm{nm1}}$ cavity mode, the interaction between the electron beam and the high-frequency electromagnetic wave takes place at the nth harmonic. Therefore, we can expect good mode selection, because mode competition with lower harmonics does not occur. This is an important advantage, because mode competition is the most severe problem in conventional high harmonic gyrotrons.

In the LOGs developed in the past, the axis-encircling electron beam is generated by the nonadiabatic effect of the cusp field [13] or the electron cyclotron resonance acceleration of electrons in along the axis of the gyrotron [14]. In both cases, the resulting electron beams have large values of ripple, that is, the displacement of guiding center from the center axis of a resonant cavity is large. This effect reduces the operation efficiency and increases the starting current for high harmonic operation.

Instead of such methods, we are using a novel system of electron gun and magnetic field that gradually changes direction to generate an axis-encircling electron beam with small ripple. As a result, we have successfully achieved third and fourth harmonic operation using rather small beam current [15].

III. EXPERIMENTAL APPARATUS AND PROCEDURES

Fig. 1 shows a schematic drawing of the LOG with the permanent magnet.

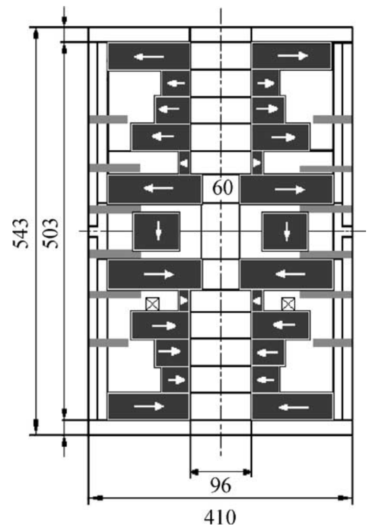

Fig. 2. Structure of the permanent magnet. The magnetization of each element is shown by an arrow. Dimensions are in millimeters.

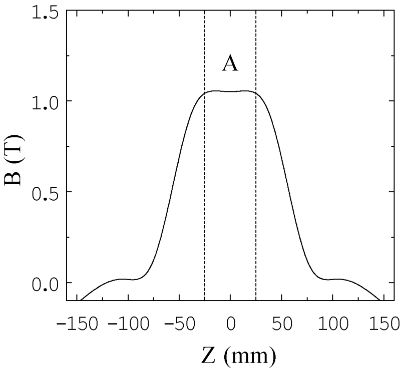

Fig. 3. Profile of the magnetic field intensity along the center axis.

A. Magnet System

The permanent magnet consists of many elements of NdFeB as shown in more detail in Fig. 2. The structure is carefully designed to generate an appropriate profile of magnetic field on the center axis of the magnet system. Each NdFeB layer is divided into 12 elements in the azimuthal direction. An arrow indicates the direction of magnetization of each layer. The resulting field profile along the center axis is shown in Fig. 3. The measured maximum field intensity is 1.0729 T and the uniformity in the region indicated by “A,” the cavity region, is better than 2%. The magnet system has an additional coil in the electron gun region to control the profile of magnetic field there. The coil consists of ten layers, each of ten turns. The coil current can be fixed at values between -13 A and $+13$ A. The additional field intensity near the cathode is 7×10^{-4} T/A.

B. Gyrotron Tube

Fig. 4 shows the structure of the LOG tube. Electrons are emitted from a circular area on the cathode surface made of LaB_6 and accelerated by the potential difference between the cathode and the body of the gyrotron. Electrons feel gradually increasing magnetic field and get vertical energy. Finally, an axis-encircling electron beam is formed and injected into the cavity. This may of producing the axis-encircling beam is quite

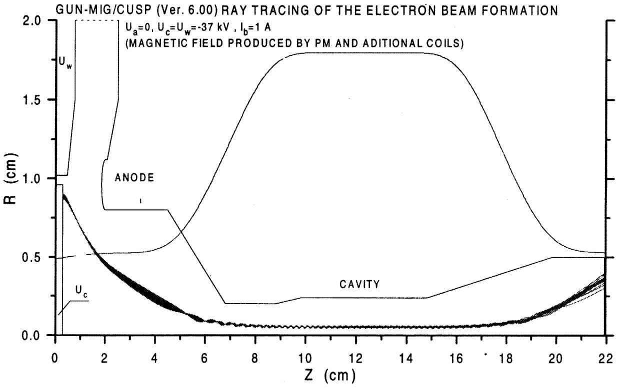

Fig. 4. Schematic drawing of the gyrotron tube.

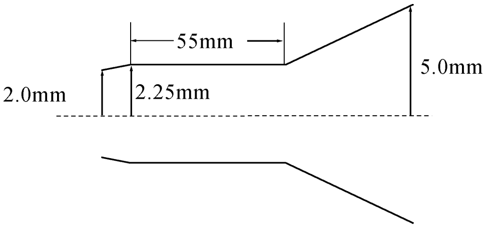

Fig. 5. Profile of cavity I.

different from other LOGs [13], [14]. The whole tube is demountable, so, we can change every component including the cavity, window, and electron gun.

For nth harmonic operation, the cavity should be designed so that the resonant frequency of the TE_{n11} cavity mode is equal to n times the electron cyclotron frequency. Fig. 5 shows the detailed dimensions of the cavity, cavity I, which was optimized for fourth harmonic operation. In this cavity, TE_{411} cavity mode is excited near the field intensity of 1 T.

An additional coil is installed in the cavity region to control the field intensity there. The coil consists of 7 layers and a total of 74 windings. This coil is pulsed. The pulse width is 18 ms and repetition rate is 1 Hz. The coil current can be changed from -20 A to $+20$ A and the additional field intensity at the cavity is 6.98×10^{-3} T/A.

The inside of the tube is pumped out by an ion pump and a turbo molecular pump. The pressure is kept at 10^{-7} torr. The electromagnetic wave generated in a cavity is transmitted along a circular and is emitted from a boron nitride vacuum window.

C. Experimental Procedure and Conditions

The gyrotron operation is in pulsed. The typical pulse width is 1 ms and the used repetition frequency in abstract is 1 Hz. The maximum acceleration voltage and beam current are 40 kV and 1.5 A, respectively.

A pyroelectric detector is used to monitor the gyrotron output. In order to observe an emission pattern, an array of pyroelectric detectors is mechanically swept over an area about one meter above the output window.

The absolute value of output power is measured calorimetrically by a water load, in which a comparison is made with heating by a 1 W electric heater. Frequency measurement is by a cylindrical cavity frequency meter or a Fabry–Perot interferometer.

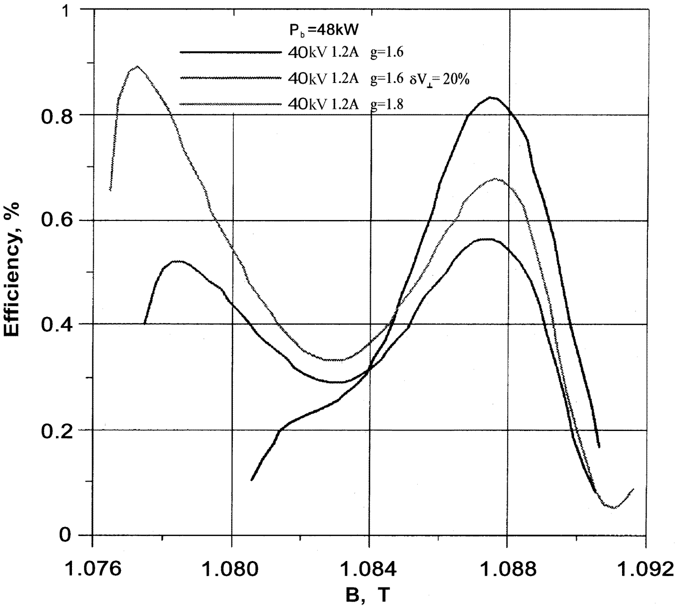

Fig. 6. Computed efficiencies as a function of magnetic field intensity B.

IV. Experimental Results

We have already completed the preliminary tests of two cavities. Cavity 1 was optimized for fourth harmonic operation using the TE_{411} mode, while cavity 2 was optimized for third harmonic using the TE_{311} mode. The test results are as follows.

A. Cavity 1 for Fourth Harmonic Operation

As described in the previous section, in the $\mathrm{TE}_{411}d$ cavity made cavity 1 was designed for the fourth harmonic operation.

In Fig. 6, computed efficiency as a function of magnetic field intensity at the cavity is presented. [15] The parameter g is the pitch factor of the beam electrons. From these results, it is expected that the fourth harmonic operation will be optimized near 1.08 T. The efficiency should be less than 1%.

In Fig. 7, a set of typical experimental results are shown. It is seen that the operation is stable throughout the pulse. The pulse length is about 1 ms and repetition rate is 1 Hz. The acceleration voltage is 40 kV and the beam current is around 1.2 A. The output power was 0.47 kW. The corresponding efficiency is about 0.98%. The frequency measured by a frequency meter was 112.696 GHz.

The output power is plotted in Fig. 8 as a function of acceleration voltage V and in Fig. 9 as a function of the magnetic field intensity B. The parameter is the current I_{gc} in one of the coil layers installed at the electron gun. When I_{gc} is changed, the pitch factor of the beam electron g changes. This results in a change of efficiency. In the both figures, the corresponding electron cyclotron frequency f_c is indicated above the graphs. Both results are similar to the computer simulation results shown in Fig. 6.

Fig. 10 shows an emission pattern measured 1030 mm above the output window. A kind of standing wave structure in the azimuthal direction is seen. This means a counterrotating TE_{411}^{-}

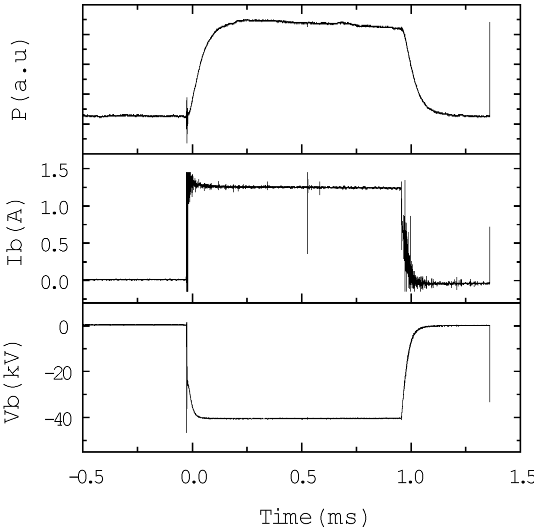

Fig. 7. Observed patterns on an oscilloscope for fourth harmonic operation using the TE_{411} cavity mode. Output power (P), acceleration voltage (V), and beam current (I) are shown.

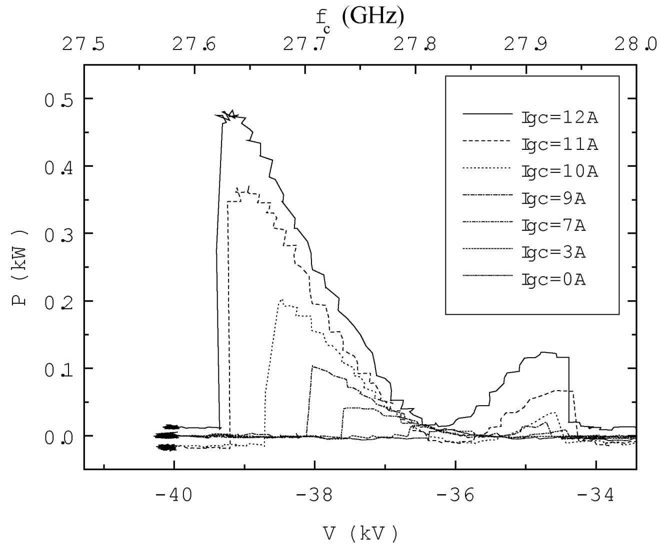

Fig. 8. Output power P as functions of cyclotron frequency f_c (acceleration voltage Vb is varied.).

mode coexists with a rotating mode TE^{+}_{411}. From the observed emission pattern, the fractions of the counterrotating and rotating modes were estimated to be 5% and 95%. The appearance of the counterrotating mode was not expected and we are studying why the mode is present.

Third harmonic operation in the TE_{311} mode has also been achieved by cavity 1 at a slightly higher field intensity. Fig. 11 shows the output power P as a function of magnetic field intensity B. There are several peaks of output power. The three peaks appearing from 1.15 to 1.2 T are third harmonic operation due to excitation of the TE_{311}, TE_{312}, and TE_{313} cavity modes. The measured frequency for the TE_{311} mode is 89.3 GHz. Frequencies for TE_{312} and TE_{313} are slightly higher. The two peaks appearing below 1.1 T correspond to the fourth harmonic operation due to excitation of the TE_{411} and TE_{412} modes.

The output power for the mode TE_{311} was 1.7 kW. The efficiency was is 3.3%.

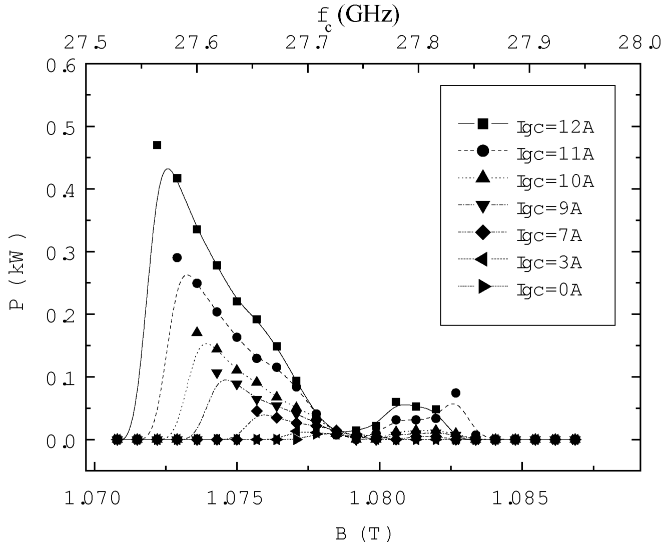

Fig. 9. Output power P as a function of the cyclotron frequency fc (field intensity B is varied.).

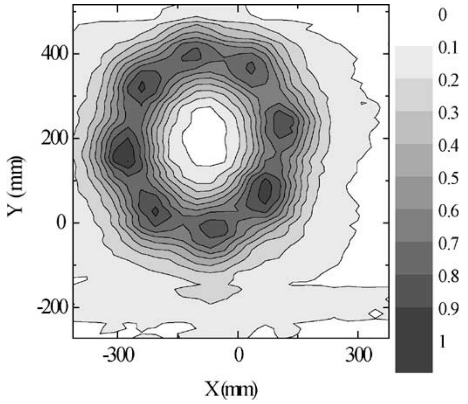

Fig. 10. Emission pattern observed at 1030 mm above the output window for fourth harmonic operation of cavity I in the TE_{411} cavity mode.

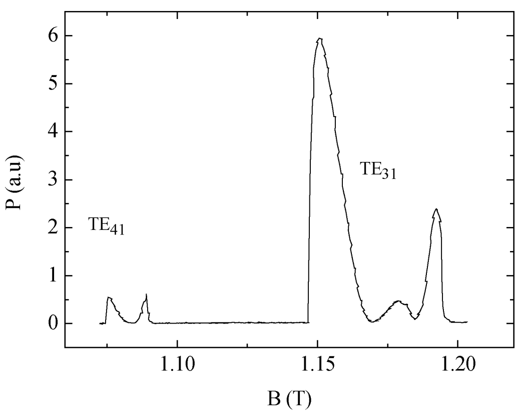

Fig. 11. Output power as a function of magnetic field intensity.

Cavity I has also achieved the fifth harmonic operation with the excitation of the TE_{511} cavity mode. However, the output power is rather low, of the order of 10 W. The frequency in this case measured by a Fabry–Perot interferometer was 138 GHz. Fig. 12 shows one of measured Fabry–Perot interferometer patterns. The frequency was determined from the spacing between the peaks.

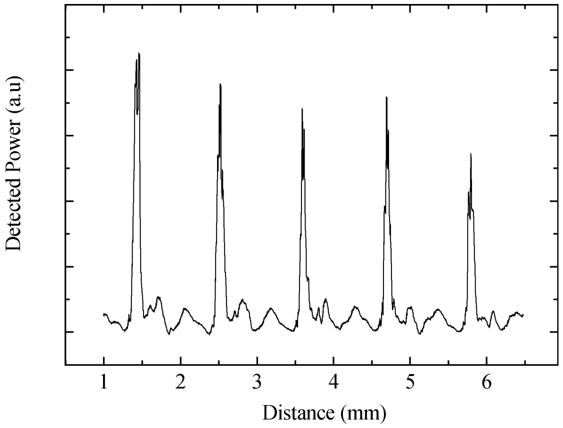

Fig. 12. A Fabry–Perot interferometer pattern for the fifth harmonic operation of cavity I in the TE_{511} cavity mode. $V_b = 40$ kV, $I_b = 1.2$ A, $B = 1.037$ T, $\lambda = 2.17$ mm, and $f = 138$ GHz.

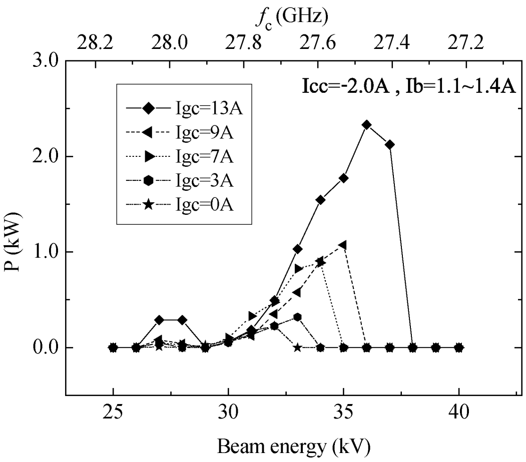

Fig. 13. Output power as a function of cathode voltage for operation at third harmonic of the cyclotron frequency of cavity 2 in the TE_{311} cavity mode.

B. Cavity 2 for Third Harmonic Operation

Cavity 2 was designed for third harmonic operation in the TE_{311} cavity mode. The radius and length were 2.36 and 50 mm, respectively.

In Fig. 13, the output power P of third harmonic as a function of the acceleration voltage V_b is shown with the current in one of the electron gun coil layers I_{gc} as a parameter. When V_b is changed, the electron cyclotron frequency f_c changes as well. The range of f_c where the fourth harmonic operation occurs broadens as I_{gc} is increased. The maximum power is 2.5 kW and the corresponding efficiency is 6.25%. The increase of the pitch factor as I_{gc} is increased affects the efficiency and the output power. The measured frequency is 84.88 GHz.

Fig. 14 shows an emission pattern for this mode. A feature of pure TE_{311} mode appears in the emission pattern. It is a manifestation of good mode selection in LOG. This is one of important advantages of LOG for development of high harmonic gyrotron.

V. CONCLUSION

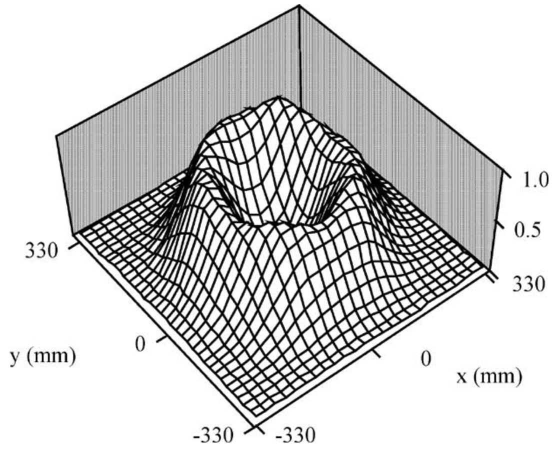

Fig. 14. Emission pattern observed at 1030 mm above the output window for third harmonic operation of cavity 2 in the TE_{311} cavity mode.

We have constructed a large orbital gyrotron (LOG) with a permanent magnet system. The electron gun and the profile of the magnetic field were optimized for the generation of a high-quality axis-encircling electron beam with a small ripple and large pitch factor.

Experimental tests of two cavities were carried out successfully. Cavity 1 which was optimized for the fourth harmonic operation in the TE_{411} cavity mode, delivered output power of 0.47 kW, corresponding to an efficiency of 0.96% and a frequency of 112.7 GHz. We have cavity I also operated at the third harmonic with output power is 1.7 kW, corresponding to an efficiency of 3.3% and a frequency of 89.3 GHz. Cavity 2 which was optimized for the third harmonic operation in the TE_{311} cavity mode. Delivered output power of 2.5 kW, corresponding to an efficiency of 6.25% and a frequency of 84.88 GHz was typically in 40 kW. Operation was pulsed. The pulse width was 1 ms and repetition rate was 1 Hz. Acceleration voltage and beam current are 1.2 to 1.3 A.

Cavity 1 also operated at fifth harmonic in the TE_{511} cavity mode. With rather low output power, of the order of 10 W and a frequency of 138 GHz.

Operations at the third, the fourth, and the fifth harmonics were achieved under acceleration voltage of only 40 kV. At the present, the frequency is ranged in millimeter-wave length region. In the future, we plan to construct a LOG with a superconducting magnet system in order to increase the frequency beyond 1 THz.

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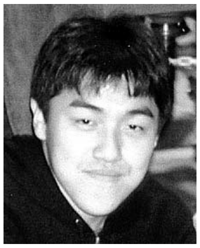

Yousuke Iwata was born in Aichi, Japan, on January 8, 1979. He received the B.S. and M.S. degrees in engineering from Fukui University, Fukui, Japan, in 2001 and 2003, respectively.

After graduating from Fukui University, he joined Mitsubishi Electric Company, Hyogo-ken, Japan, as a Researcher. His research interests include the development of submillimeter-wave gyrotrons.

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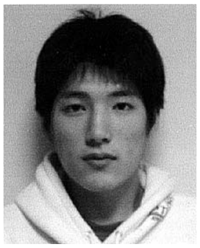
His research interests include the development of submillimeter-wave gyrotrons.



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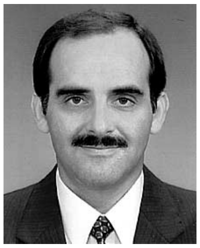

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