Achievement of High Power Sub-Terahertz Radiations with a Second Harmonic Gyrotron

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High power, single mode oscillations from a sub-terahertz gyrotron, at a second harmonic, were successfully demonstrated with pulse operation. A powerful electron gun was applied to attain high power oscillation. The resonant modes were selected carefully enough to oscillate singly and the cavity shape was optimized for the resonant modes to interact efficiently with an electron beam generated by the electron gun. Optimizing the operational parameters produced output powers of 33 and 27 kW, at frequencies of 349 and 389 GHz, respectively—the highest oscillation powers obtained to date in the sub-terahertz frequency region.

Keywords: gyrotron, sub-terahertz technology, electron cyclotron maser, collective Thomson scattering

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The gyrotron is a fast wave gyro device that uses the electron cyclotron maser instability. Gyrotron research has progressed in obtaining high power and high frequency oscillations. High power gyrotrons with frequencies lower than 170 GHz have been developed for heating and current drive of nuclear fusion plasmas [1, 2]. High frequency gyrotrons have also been developed for application to various research fields [3–5]. Recent nuclear fusion research has focused on collective Thomson scattering (CTS) as a sophisticated method of diagnosing the dynamics of ions and alpha particles. Realizing CTS requires a coherent radiation source of both high power and a high frequency to acquire sufficient spatial resolution and signal to noise (SN) ratios. Applying a gyrotron to CTS in a large helical device demands a frequency of around 400 GHz at power levels of 100 kW and a pulse duration of 1 μs [6, 7]. Generating 400 GHz at the fundamental resonance requires a superconducting magnet that can produce a magnetic field of roughly 16 T. Such magnets are expensive and not available easily. Hence, development of second harmonic high power pulse gyrotron began by combining an existing 8 T superconducting magnet and a powerful electron gun. In particular, the optimum mode was carefully selected to allow the mode to oscillate efficiently and stably even under operational conditions with high voltages and high beam currents. We have demonstrated single mode pulse oscillation at more than 30 kW at the second harmonic resonance. This shows a possibility of achieving the final goal of 100 kW. This paper describes the initial findings for results of the development of a high power second harmonic pulse gyrotron with a frequency of around 400 GHz.

To use a gyrotron as a CTS radiation source and oscillate it stably, single mode oscillation is required. The most difficult part of achieving the single mode oscillation at the second harmonic is the competition with other modes, including fundamental modes. This is because the second harmonic modes are much denser than the fundamental modes. Shrinking the cavity radius is effective against mode competition. A smaller radius cavity can improve the degree of mode separation between neighboring modes, since the difference in resonant frequency for nearby cavity modes $\Delta f_{\rm cav}$ becomes

$$\Delta f_{\rm cav} \propto \left|\chi'_{mn\_1} - \chi'_{mn\_2}\right| \cdot R_{\rm cav}^{-1}.$$

Here, $R_{\rm cav}$ and $\chi'_{\rm mn}$ stand for the cavity radius and the nth zero of the derivative of the mth order Bessel function, respectively. The cavity radius was determined to be 2.99 mm—about one-tenth that of conventional high power gyrotrons. Then, some second harmonic modes, well isolated from other modes, were selected as candidate modes for oscillation by surveying the eigen values for many TE modes. In selecting the mode, both the degree of isolation and the eigen value are crucial for generating around 400 GHz, once the cavity radius is fixed. In addition, compatibility between the RF-electric field profile and cross-sectional position of the electron beam passing into the cavity should be considered [8]. We determined that both the $TE_{6,5,1}$ and $TE_{8,5,1}$ modes, with resonant frequencies of 350 and 390 GHz, respectively, met the requirements and should provide single mode oscillation.

To accomplish single mode oscillation with high efficiency, it is critical that the cathode magnetic field is adjusted properly ensuring that the electron beam interacts as efficiently as possible with the electric field in the cavity. The cathode magnetic field is mainly controlled by an auxiliary normal conducting coil surrounding the electron gun.

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When the existing electron gun is operated with a gun coil current of around 160 A, it can produce a good quality laminar flow beam without remarkable velocity spread [9]. As a result, the flux conservation law produces a beam radius of nearly 1.9 mm in the cavity region. This beam radius does not coincide with the first peak, but with the second peak of the beam-field coupling for both modes. However, the total oscillation efficiency, calculated based on a nonlinear single mode theory [10], is high enough, if the cavity length and the beam current are properly selected. For example, setting the cavity length to 12 mm resulted in a total oscillation efficiency of 14% for a beam current of 5 A.

After designing the cavity, a demountable gyrotron was fabricated and operated to investigate its oscillation characteristics. The gyrotron has no inner mode converter and its oscillation is radiated via an output vacuum window made of a single crystal sapphire. Dependence of radiation intensity on the magnetic field strength at the cavity with a cathode voltage of 60 kV, beam current of 5 A, anode voltage of 43 kV, and gun coil current of 150 A, is shown in Fig. 1 (a). Here, each voltage is defined with respect to the grounded collector. The pulse width is 1 μs in the experiment, and the radiation output was guided from the vacuum window to a pyroelectric detector. The signal intensity given in Fig. 1 is the averaged power during 1 μs at each magnetic field. A high-pass filter with a cut-off frequency of 308 GHz was inserted in front of the pyroelectric detector; the oscillation is shown in Fig. 1 (b). Thus, the detected signals in Fig. 1 (b) are expected to be second harmonic oscillations. Theoretical calculations strongly suggest that oscillations at 6.9 and 7.75 T represent the $TE_{6,5,1}$ and $TE_{8,5,1}$ modes, respectively. Actual frequencies for the two modes were measured with a Fabry-Perot interferometer and identified as 349 and 389 GHz, respectively. They were both lower than the cavity resonance frequencies by about 1 GHz. Such subtle shifts in frequency may be derived from a fabrication error of the cavity radius of less than 10 μm. Single mode oscillations of them were also confirmed in parallel from the interference waveforms.

Power measurement was carried out using a water load installed just outside of the vacuum output window. Radiation power was deduced from the rate of temperature rise of water when the gyrotron was operated at a pulse width of 1 μs and a repetition rate of 10 Hz. To find the optimum condition for high power oscillation, the beam current, cathode voltage, beam injection radius, and the anode voltage were fine tuned. Then, maximum powers of 33 and 28 kW were obtained for the $TE_{6,5,1}$ and $TE_{8,5,1}$ modes, respectively. In the estimations, reflections for approximately 400 GHz electromagnetic waves by water were taken into consideration. But, these are lower limit values, since reflections by a water vessel made of glass were not considered. Figure 2 shows the current status for the power and frequencies achieved with second harmonic oscillations [11]. Most of the data in Fig. 2 was obtained with pulse operation. The closed circles indicate data established by Fukui University. Our new results have broken the existing power records, even around 400 GHz.

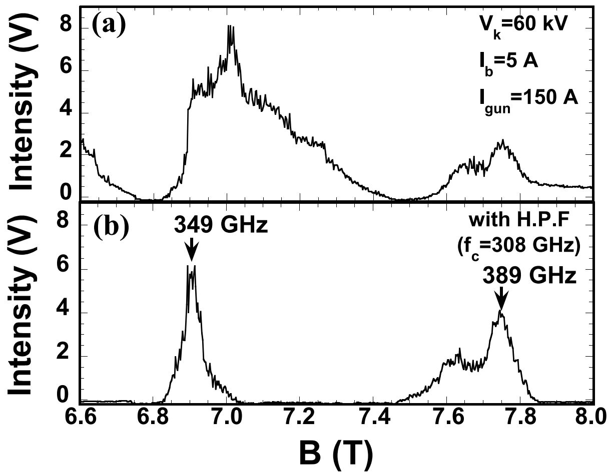

Fig. 1 Dependence of radiation intensity on the magnetic field strength at the cavity: (a) without a high pass filter, and (b) with a high pass filter.

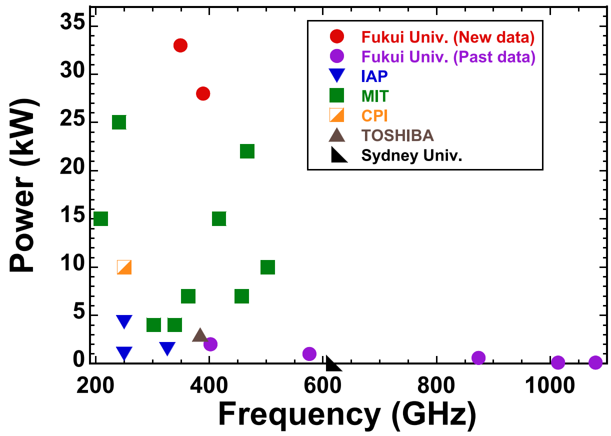

Fig. 2 Radiation power achieved as a function of frequency, for second harmonic gyrotrons.

The total oscillation efficiency is about 10%, somewhat lower than the 14% predicted from the theory. Using a vacuum window with an inappropriate thickness may be one main cause for the degradation. The design of a higher efficiency gyrotron is now underway.

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