Study of 1-THz 4th-Harmonic Gyrotron

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***Abstract*—A preliminary design of a 1-THz gyrotron based on the fourth harmonic operation is presented. The cylindrical-waveguide $TE_{4,8}$ mode is selected as the operating mode. Considering the weak beam-wave coupling strength in a 4th-harmonic open-cavity interaction circuit at the frequency of 1 THz, this paper proposes applying low-temperature cooling, for example applying liquid nitrogen, to increase the limit of the Q factor and extend the effective length of the cavity resulting in a significant enhancement of the interaction efficiency and suppression of ohmic losses. Applying multi-mode time-domain theory in the simulation, it was found that although the competing third-harmonic $TE_{3,6}$ mode was excited first, the fourth-harmonic $TE_{4,8}$ mode finally dominates in the steady state regime.**

***Index Terms*—Electron cyclotron maser, gyrotron, ohmic loss, quality factor, sectioned cavity, terahertz.**

I. Introduction

Terahertz(THz) waves, occupy a part of the electromagnetic spectrum, which plays an important role in this frequency band giving rise to many potential applications, e.g., high resolution imaging, plasma fusion diagnostics[1] and dynamic nuclear polarization enhanced nuclear magnetic resonance[2]. Traditional vacuum electronic devices operate normally at frequencies lower than the millimeter wave band, while traditional optical devices operate normally at frequencies in the infrared band or higher. As a result, the band between millimeter waves and infrared waves there is a spectral gap known as the "THz gap". To fill this gap scientists with experience in the generation of electromagnetic radiation at microwave frequencies are trying to extend the operating frequency from the microwave band to the THz band, while those working in optics are devoting resources to lowering the operating frequencies to the THz band from the infrared sources they have traditionally worked on[3]. However, optical devices such as quantum cascade lasers and pumped terahertz lasers are low power, usually not larger than a milliwatt[3].

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Gyrotrons are a kind of vacuum electric device based on the principle of the electron cyclotron maser [4]. To extend the operating frequency higher than 1 THz, some experimental designs have been proposed. A second-harmonic, 1.005-THz gyrotron was confirmed experimentally with a $TE_{6,11}$ cavity operating mode using a 19.0-T pulse magnet at the University of Fukui, Japan [5]. Another experiment designed, manufactured and tested at the Institute of Applied Physics, Russia Academy of Sciences [6]generated 1.5kW of coherent radiation at 1.022 THz. The power is generated due to the fundamental harmonic interaction, as a result of which, the external magnetic field was as high as 38.5 T. The experiments mentioned above in Japan and Russia both necessitate >19T magnetic fields. To lower the value of the external magnetic field, we propose a design of a 1-THz gyrotron with the fourth-harmonic interaction. The paper is organized as follows. In Section II, low-temperature cooling is introduced to reduce the ohmic loss. In Section III, a sectioned cavity is analyzed based on a single-mode frequency-domain theory. In Section IV, the results of dynamic simulation to analyze the mode competition are presented. Section V summarizes the main conclusions of the work.

II. Low Temperature Cooling

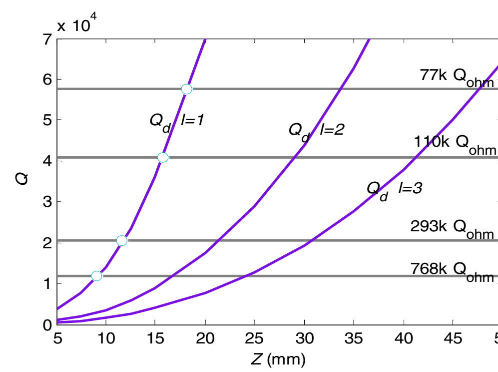


Fig. 1 Diffraction Q-factors under various temperatures. The abscissa is the length of interaction circuit. *l* is the order of axial modes. The gray solid lines indicate the ohmic Q-factor at different temperatures with the unit in Kelvins.

The output power will decrease rapidly due to the ohmic loss[7]. To diminish the ohmic loss caused by the thermal effect, we propose to lower the temperature of the interaction circuit. The total quality factor (Q-factor) can be determined as follows,

$$1/Q = 1/Q_d + 1/Q_{ohm} \quad (1)$$

while Q is the total Q-factor, Q_d and Q_{ohm} is diffraction Q-factor and ohmic Q-factor, respectively. Q_d at different interaction lengths are calculated based on the single-mode frequency-domain theory [8] and are shown in Fig. 1. With the increase of the interaction length, the diffraction Q-factor is increased. However, the total Q-factor is dominated by the Ohmic Q-factor. With the decrease of the circuit temperature as well as the ohmic loss, the upper limit of Q-factor is increased. The start oscillation currents are calculated as demonstrated in Fig. 2. The start oscillation currents of $TE_{3,6}^{(3)}$ and $TE_{4,8}^{(4)}$ modes are lower than the operating current, i.e., 0.7A, thus, further analysis needs to be implemented for evaluating the mode competition. The superscript indicates the harmonic number.

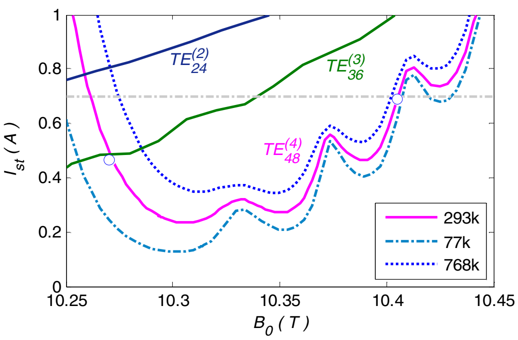
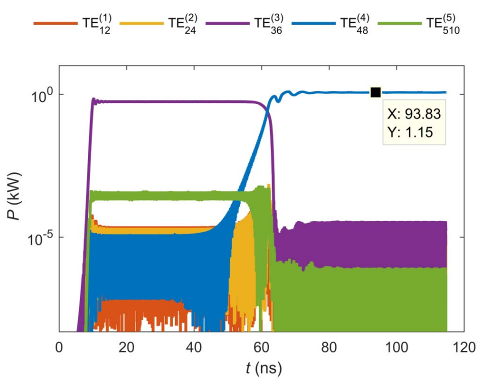
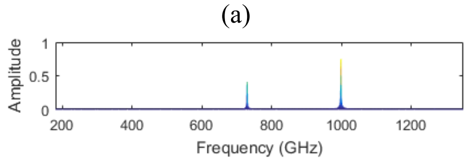


Fig. 2 Start oscillation currents at different temperatures. The gray dash-dotted line is the operating current produced by the electron gun, i.e., 0.7A.



(a)



(b)

Fig. 3. (a) The dynamic calculation results and (b) is the frequency spectrum.

III. Dynamic Analysis

An 80-kV, 0.7-A electron beam is applied to excite the fourth harmonic gyrotron. The pitch factor of the electron gun is 1.5, and the velocity spread is 10%. The results are verified by the Finite Element Method simulation with the operating mode selected here the $TE_{4,8}^{(4)}$ mode, To analyze the mode competition between the $TE_{4,8}^{(4)}$ mode and adjacent modes, the dynamic simulations were carried out using a multi-mode time-domain program [8]. The results are presented in Fig. . According to the start oscillation currents demonstrated in Fig. 2, the dominant competition modes is between the $TE_{3,6}^{(3)}$ and $TE_{4,8}^{(4)}$ modes. Since the latter has a lower starting oscillation current than the former, the $TE_{3,6}^{(3)}$ can be suppressed and the $TE_{4,8}^{(4)}$ mode prevails existing in the final steady state. The output power of $TE_{4,8}^{(4)}$ mode is five orders of magnitude higher than those of the $TE_{3,6}^{(3)}$, $TE_{510}^{(5)}$, $TE_{1,2}^{(1)}$ and $TE_{2,4}^{(2)}$ modes. From the frequency spectrum calculated from the Fourier transform, power around 750 GHz is generated by $TE_{3,6}^{(3)}$ mode and the the $TE_{4,8}^{(4)}$ mode dominates 1 THz.

IV. Conclusion

The 1-THz 4th-harmonic gyrotron is theoretically studied. Due to strong ohmic loss at a high frequency, this paper proposes applying low-temperature cooling to increase the material conductivity and suppress the ohmic loss. A longer cavity with a higher Q factor is feasible operating in a low temperature condition, which will greatly enhance the interaction strength of the 4th harmonic interaction. A preliminary design of 1-THz, 4th-harmonic gyrotron using $TE_{4,8}^{(4)}$ mode and dynamic simulations have been carried out to analyze the mode competition between the operating modes and various competition modes. Due to the lower start oscillation current of $TE_{4,8}^{(4)}$ mode than the other modes, the $TE_{4,8}^{(4)}$ mode gradually becomes the dominant mode in the steady state regime. An output power of 1.15kW excited by an 80-kV 0.7-A axis encircling electron beam has been predicted.

V. Acknowledgements

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