Simulation of a 0.33-THz Second Harmonic Gyrotron Based on Double Confocal Cavity

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Abstract: *Confocal cylindrical waveguide performs many good characters, such as big power capacity and low mode density, which are good for designing high harmonic terahertz gyrotron. Motivated by improving beam-wave interaction efficiency of quasi-optical gyrotron, a novel gyrotron beam-wave interaction structure based on double confocal waveguide has been proposed and theoretically analyzed in this paper. A 0.33 THz second harmonic gyrotron oscillator based on double confocal cavity has been designed and simulated by PIC code. It is indicated that double confocal cavity is able to enhance the output power and the interaction efficiency of quasi-optical gyrotron. Besides, the mode characteristic of double confocal waveguide is investigated with the simulation results.*

Keywords*:* gyrotron, high harmonic, double confocal cavity, terahertz

Introduction

Gyrotron oscillator, based on the principle of electron cyclotron maser (ECM), is one of the most powerful radiation sources in millimeter-wave and terahertz band, and has been widely applied in many fields, such as high-resolution radar, plasma heating for nuclear fusion, nondestructive testing, and plasma diagnoses.

As a type of open structure, quasi-optical cylindrical confocal waveguide performs low mode density and good mode selective characters, which offer a distinctive advantage in high frequency gyrotron design. Recently years, the research group of R. J. Temkin in Massachusetts Institute of Technology (MIT) first applied this structure into a fundamental gyrotron oscillator and a series of 140 GHz confocal gyrotron traveling wave amplifiers [1] for the application of Dynamic Nuclear Polarization (DNP) enhanced Nuclear Magnetic Resonance (NMR) spectroscopy. A 0.4 THz harmonic gyrotron based on confocal cavity also has been developed in the Terahertz Research Center, University of Electronic Science and Technology of China (UESTC) [2]. Initial experimental results demonstrated that the gyrotron prototype could be stable operated at TE0,11 confocal mode interacted with the second harmonic of electron and achieved 6.44 kW output power with a 3.4% efficiency.

However, because of the non-uniformity of transverse field distribution, only a part of gyrating electrons located in regions of strong electronic field intensity can take part in the beam-wave interaction [3], the total beam-wave interaction is not efficient in confocal cavity. To improving electron efficiency of quasi-optical gyrotron, a novel terahertz harmonic gyrotron interaction structure based on double confocal waveguide is proposed and analysed in this paper. The design of a 0.33 THz second harmonic gyrotron oscillator based on double confocal cavity is presented.

Gytorton Cavity Design

The initial design of double confocal cavity operated at 0.33 THz second harmonic has been reported in [3], in which a cylindrical tapered waveguide is employed as the down-tapered section. To reduce the electromagnetic wave reflection between the down-tapered section and the straight section, an improved double confocal cavity is proposed in this paper. As shown in Fig. 1, the down-tapered section in this new gyrotron cavity utilizes a double confocal tapered waveguide. The detailed designed structure parameters of the 0.33 THz second harmonic gyrotron cavity are listed in Table I.

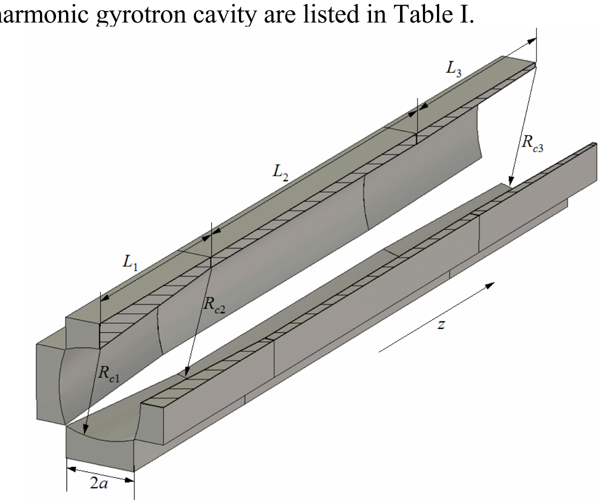

Fig. 1. Structure scheme of the double confocal cavity.

This work was supported in part by the National Key Research and Development Program of China No. 2019YFA0210202, in part by the National Natural Science Foundation of China under Grant 61971097 and Grant 61771096, in part by the Sichuan Science and Technology Program No. 2018HH0136, and in part by the Terahertz Science and Technology Key Laboratory of Sichuan Province Foundation No. THZSC201801.

TABLE I. Design parameters of the double confocal cavity.

Parameter	Value
Frequency	330 GHz
Operation mode	$TE_{0,11}$
Cyclotron harmonic (s)	2nd
Mirror aperture ($2a$)	3.6 mm
Down-tapered length (L_1)	9 mm
Straight length (L_2)	17 mm
Up-tapered length (L_3)	10 mm
Input mirror radius (R_{c1})	4.48 mm
Straight mirror radius (R_{c2})	5.10 mm
Output mirror radius (R_{c3})	5.60 mm

Simulation Results

The designed double confocal gyrotron cavity has been simulated by a 3-D Particle-In-Cell (PIC) code, CHIPIC, developed by UESTC. During the simulation, the given set of electron beam parameters are: operation voltage $V_0 = 40$ kV, beam current $I_b = 2$ A, guiding center radius of $R_b = 1.65$ mm, and velocity ratio $\alpha = v_\perp/v_z = 1.5$, neglecting the beam velocity spread.

PIC simulation results verified that the double confocal cavity was stably operated at the second harmonic of $TE_{0,11}$ mode without mode competitions and output a single frequency of 328.93 GHz. By changing the magnetic field B_0, the simulation results of output power in double confocal gyrotron cavity are shown in Fig. 2. The peak output power is about 9.9 kW at the magnetic field B_0 of 6.255 T, corresponding to an interaction efficiency of 12.4%. Under the same mirror structure and beam parameters, the maximum output power of single confocal cavity is only 4.2kW with a 5.3% interaction efficiency. PIC simulation results demonstrate the function of double confocal cavity to enhance the gyrotron output power and interaction efficiency.

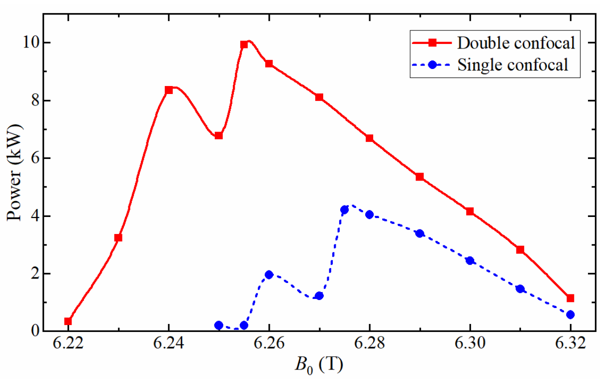

Fig. 2. Simulation results of output power for single confocal cavity and double confocal cavity as functions with the magnetic field B_0.

To study the detailed beam interaction in double confocal cavity, the time variation of E_x and E_y at the output port of double confocal cavity are compared and plotted in Fig. 3. The results show that E_x is first excited in double confocal cavity. As oscillation gets stable, the time difference between E_x and E_y is about 0.76 ps, corresponding to a quarter of wave period at oscillation frequency 328.93 GHz ($T = 3.04$ps), as shown in Fig. 3(b). It is suggested that there is a π/2 phase difference between the horizontal and vertical $TE_{0,11}$ confocal mode.

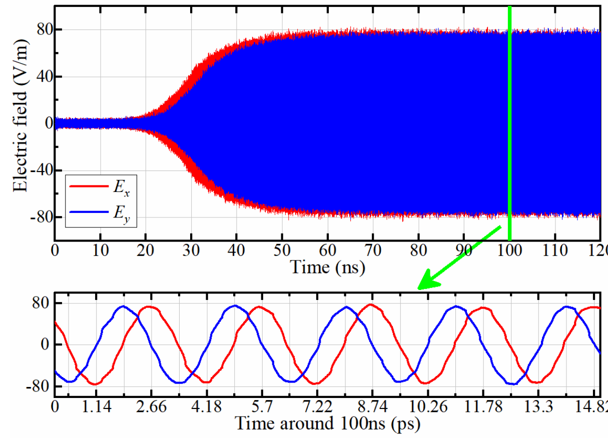

Fig. 3. Time variation of the output field E_x and E_y for double confocal cavity: (a) over all the simulation time; (b) expanded results around 100 ns.

The non-synchronous time variation of E_x and E_y indicates that the eigen mode in double confocal waveguide is a kind of hybrid mode superimposed of two independent single confocal waveguide modes. In principle, if the two pairs of confocal mirror is different and well-designed, the horizontal confocal mirrors can be operated at one cyclotron harmonic mode, while the vertical confocal mirrors can be operated at another cyclotron harmonic mode. Thus, the double confocal gyrotron with one electron beam will excite two frequency oscillations at the same time. When the beam radius is larger than the Gaussian beam waists, the gyrating electrons interacting with horizontal or vertical confocal mode are two totally different parts in one electron beam. So the mode competitions between two waveguide modes can be neglected, which effectively avoid the same problem in conventional gyrotrons operated at dual frequencies. In this respect, double confocal cavity provides a new possibility to develop the novel THz radiation source.

Conclusion

A 0.33 THz second harmonic gyrotron based on double confocal cavity is designed and PIC simulated in this paper. PIC simulation results demonstrate that double confocal cavity is able to improve the output power and the interaction efficiency of quasi-optical gyrotron. In addition, the results show that the eigen mode in double confocal waveguide is a kind of hybrid mode superimposed of two independent single confocal waveguide modes. Double confocal gyrotron may be operated in two modes and two cyclotron harmonics, simultaneously, with a single electron beam. This study provides the possibility to generate high power radiation in THz band.

References

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