Operation Characteristics of Microwave Sources Based on Slow-Wave Interaction in Rectangular Corrugation

Y. Takamura, Y. Kazahari, H. Oe, K. Ogura, A. Sugawara, M. Hirata[a]

Graduate School of Science and Technology, Niigata University, Niigata 950-2181, Japan
[a] Plasma Research Center, University of Tsukuba, Tsukuba 305-8577, Japan
(Received 15 October 2007 / Accepted 3 August 2007)

Studies of slow-wave device with a novel disk cathode and two types of rectangular corrugation are reported. The beam voltage is weakly relativistic, less than 100kV. A disk cathode can generate a uniformly distributed annular beam in the weakly relative region. Rectangular corrugation having the ratio of corrugation width to periodic length of 50% or 20% is used. By using the first one, output powers of about 200kW are obtained around 100kV. For the other, the effect of slow cyclotron resonance is observed in the low energy region around 30kV. Output powers are in the range of a few W. For the slow cyclotron maser, the operation mode between axisymmetric and nonaxisymmetric modes can be controlled by changing the end condition of rectangular corrugation.

Keywords: slow-wave device, weakly relativistic, disk cathode, annular electron beam, rectangular corrugation

1. Introduction

Slow-wave high-power microwave devices such as backward wave oscillator (BWO) can be driven by an axially injected electron beam without initial perpendicular velocity and has been studied extensively as a candidate for high or moderate power microwave sources. In the slow-wave devices, slow-wave structure (SWS) is used to reduce the phase velocity of electromagnetic wave to the beam velocity. In order to increase the power handling capability and/or the operating frequency, oversized SWSs have been used successfully. The term “oversized” means that the diameter D of SWS is larger than free-space wavelength λ of output electromagnetic wave by several times or more.

In Refs. [1] and [2], K-band and Q-band oversized BWO operating in the weakly relativistic region less than 100kV are reported. Output power in the range of hundreds of KW is obtained by using a sinusoidally corrugated SWS. However, for moderate power level of MW or less, the rectangular corrugation may be better than the sinusoidal corrugation. We propose to use a novel disk cathode made of metal only [2]. It can generate a uniformly distributed annular beam in the weakly relativistic region and is used in our slow-wave device. In this work, we use two types of rectangularly corrugated SWSs for which the ratio of corrugation width to periodic length differs. Upper cut-off frequency is about 25GHz for the both SWSs. We examine operation characteristics of the slow-wave devices based on each SWS, in high (around 100 kV) and low (around 30kV) beam energy region.

author’s e-mail: f06e090g@mail.cc.niigata-u.ac.jp

2. Cold Cathode

We use a cold cathode to obtain a beam with high current density. It is very difficult to generate a uniformly distributed annular beam by the cold cathode, especially in the weakly relativistic region less than 100kV. In the past, we have used a hollow cathode with velvet on the axsymmetric emitting edge in order to obtain an annular electron beam [1]. By controlling velvet, fairly uniform annular beams have been obtained as shown in Fig. 1. The beam shape is observed by the burn pattern on thermally sensitive paper. The average radius of the annulus is nearly the same as the cathode diameter.

Recently, the uniformity of the beam is improved much more by using a novel disk cathode. The idea of disk cathode was presented by Loza *et al* [3], and used in the relativistic region [4]. In this paper, the disk cathode is tested in the weakly relativistic region. The burn pattern is shown in Fig.1. The annular beam by the disk cathode distributed more uniformly compared with the hollow cathode with velvet. Moreover, any coating on the disk cathode surface is not required. The disk cathode is suitable for the weakly relativistic case.

Fig.1 The burn patterns of annular electron beam. Left-side is the pattern of 5-shot overlay for the hollow cathode with velvet at about 90kV. Right-side is the pattern of 1-shot for the disk cathode without velvet at about 80kV.

3. Rectangular SWS

Cylindrical SWS is periodically corrugated as shown in Fig.2. Dispersion characteristics of SWS are determined by average radius R_0, corrugation amplitude h, corrugation width d and periodic length z_0. The corrugation wave number is given by $k_0=2\pi/z_0$. The dispersion characteristics of structure are controlled by changing R_0, h, d and z_0.

Dispersion characteristics of rectangular SWS are obtained by a numerical method based on a mathematical formula in Ref. [5]. Figure 3 shows the each dispersion characteristic of axisymmetric transverse magnetic (TM_{01}) mode for type A and B, whose parameters are listed in table 1. The slow space charge mode and the slow cyclotron mode coupling to fundamental TM_{01} mode may lead to the Cherenkov and slow cyclotron instability. For type A SWS in Fig.3 (a), slow-wave device operate as BWO based on Cherenkov instability. The interacting point of beam is around the upper cut off at π-point. For type B SWS in Fig.3 (b), dispersion curve around upper cut-off at π-point becomes flat, compared with type A. And the interaction point between beam line of slow space charge mode and TM_{01} mode shifts toward traveling wave region at 80keV. Decreasing beam energy to 30keV, the interaction point moves to backward wave region.

In this work, each rectangular SWS of type A and B is used. We examine operation characteristics of the slow-wave device using each SWS in high (around 100 kV) and low (around 30 kV) energy region.

Table 1 Parameters of rectangular SWS

	R_0 [mm]	h [mm]	z_0 [mm]	d/z_0 [%]
Type A	15.1	1.1	3	50
Type B	15.38	1.38	2.2	20

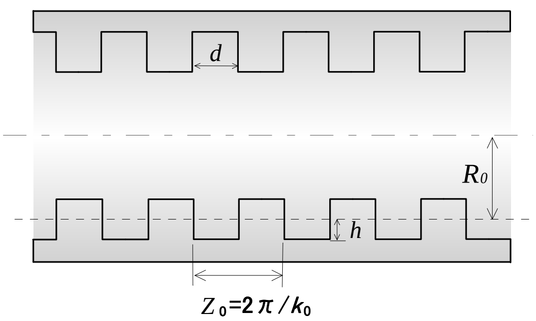

Fig.2 Periodically corrugated cylindrical SWS.

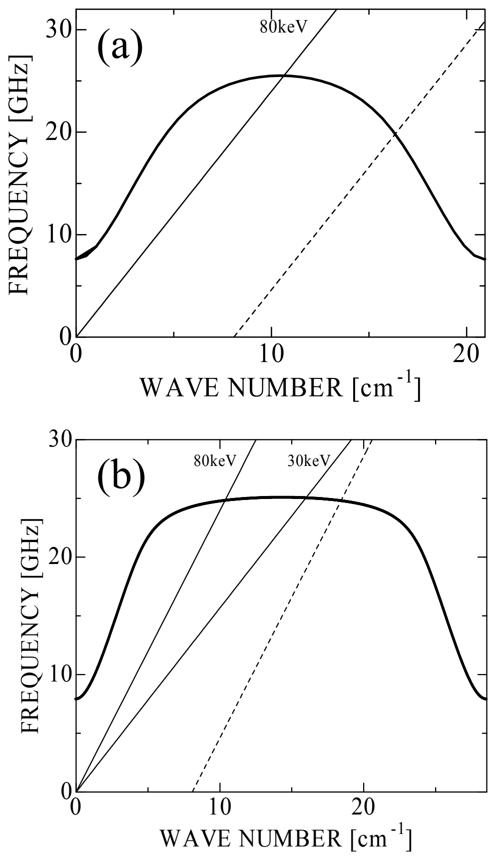

Fig.3 Dispersion characteristics of TM_{01} for rectangular SWS. (a) is for type A. (b) is type B. Solid and dashed lines are the beam line of slow space charge mode and slow cyclotron mode at 0.8T, respectively.

4. Experiment with rectangular SWS

The experimental setup is schematically shown in Fig.4. Output voltage up to 100 kV from the pulse forming line is applied to the cold cathode. A disk cathode is used as a cold cathode. A uniform axial magnetic field B_0 for the beam propagation is provided by ten solenoid coils. The value of B_0 can be changed from 0T to 0.9T. The microwave output is picked up by a rectangular horn antenna typically located 600 mm away from the output window.

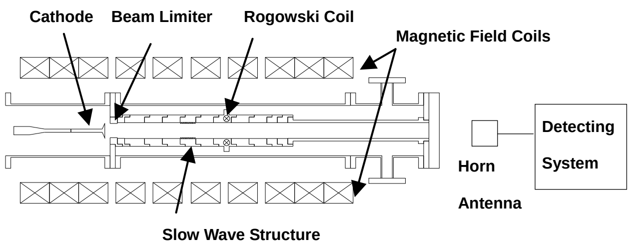

Fig.4 Schematic diagram of the experimental setup.

Figure 5 shows an example of detected signals. The beam voltage and current are about 100kV and 300A, at the microwave peak time. The operation frequency estimated from delay time is about 26GHz.

Figure 6 shows the dependence of the microwave power on the cathode voltage with type A SWS. The oscillation starting voltage is about 60kV. Output powers increase by increasing the cathode voltage. For type A SWS, the estimated maximum power is about 200kW at 100kV. For type B SWS, the microwave output can not be obtained in the high energy region from 60kV to 100kV. However, the microwave power in the range of a few W is obtained in the low energy region around 30kV, less than the oscillation starting voltage. In Fig. 7, the power dependence on the magnetic field for type B SWS is shown. The microwave outputs resonantly increase around 0.65T. This might be caused by slow cyclotron resonance as discussed later. For type A SWS, such an effect of slow cyclotron resonance cannot be observed in the low energy region, less than the oscillation starting voltage.

In our slow-wave device, both axisymmetric TM_{01} mode and nonaxisymmetric hybrid HE_{11} mode exist as a candidate of the operation mode. To examine the mode, the radiation patterns are measured by shifting the receiving horn antenna in an equatorial plane around a pivot at the center of output window. The electric fields component of E_θ and E_ϕ is measured by the horn antenna. E_θ (E_ϕ) is horizontal (vertical) component of the electric field in the equatorial plane. Figure 8 show the radiation patterns with type B SWS. The beam voltage is about 30kV. The magnetic field is 0.6T, around peaks of output in Fig.7. The operation mode changes by the straight cylinder length before SWS in Fig.4. For the straight cylinder of 34mm, the operation mode is TM_{01} mode as Fig.8 (a). By changing the straight length to 68mm, the radiation pattern changes to the pattern HE_{11} mode as Fig.8 (b). The axisymmetric and nonaxisymmetric mode can be controlled by the axial condition of SWS.

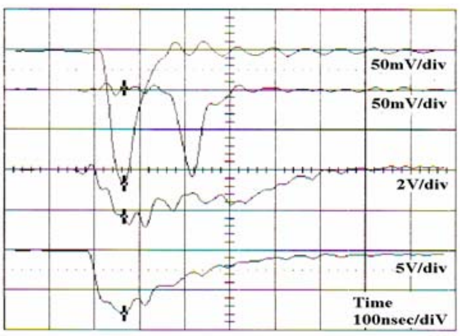

Fig.5 Waveform of measured signals: 1 prompt signal, 2 delayed signal, 3 beam current signal and 4 beam voltage.

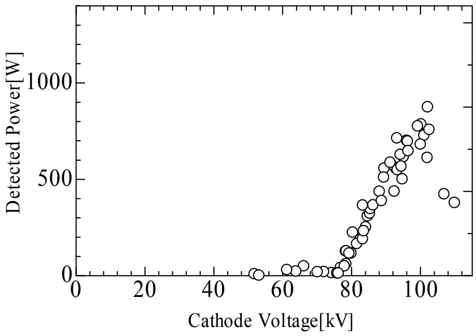

Fig.6 Output powers versus the cathode voltage for a 10-period type A SWS.

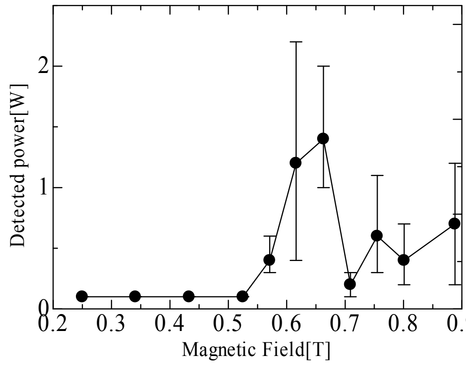

Fig.7 Output powers versus the magnetic field for a 10-period type B SWS. The beam voltage is around 30kV.

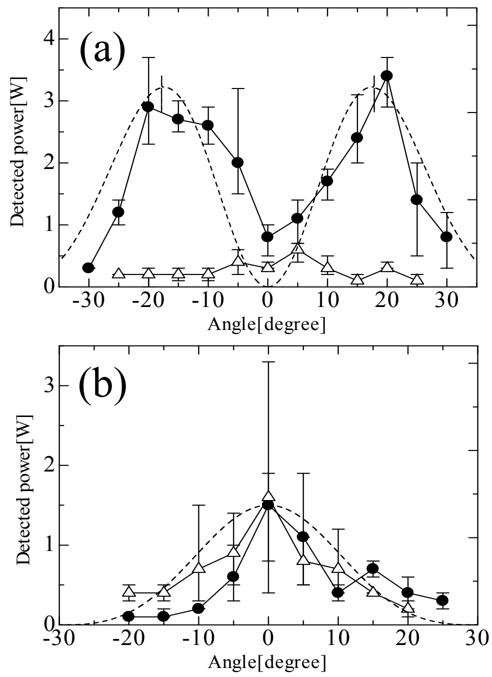

Fig.8 Radiation patterns with the straight cylinder of (a) 34mm and (b) 68mm for type B SWS. (●) and (△) are respectively E_θ and E_ϕ components. Dashed curves are theoretical curves of (a) TM_{01} and (b) HE_{11} mode, respectively.

5. Discussion and Conclusion

We study slow-wave device with a disk cathode and two types of rectangular SWS. The beam voltage is weakly relativistic, less than 100kV. We propose a novel cold cathode, which is a disk type cathode made of metal only. It can generate a uniformly distributed annular beam in the weakly relativistic region.

The estimated output power of about 200kW is obtained by using type A SWS at about 100kV. However, the microwave can not oscillate for type B SWS, because the interacting point of beam shifts to traveling wave region in high energy region around 100kV. Around about 30kV less than the oscillation starting voltage, radiations in the range of a few W is obtained. The dispersion characteristic of TM_{01} mode for type B is shown in Fig.9. Beam interactions are taken into account, based on a field theory developed in Ref. [6] for cylindrical SWS driven by an annular beam. The slow cyclotron mode depends on the axial magnetic field B_0. By increasing B_0, the beam line of slow cyclotron mode shifts to the right in Fig.9. The Cherenkov interaction resonantly synchronizes with slow cyclotron interaction at the fundamental frequency with 1.35T. This is a slow cyclotron maser operation reported in Refs. [7] and [8]. In our experiments, the resonance occurs around 0.65T and might be a combined operation of the Cherenkov and the second harmonic slow cyclotron interactions. For the slow cyclotron maser, it is demonstrated that the axisymmetric and nonaxisymmetric mode can be controlled by changing the end condition of SWS.

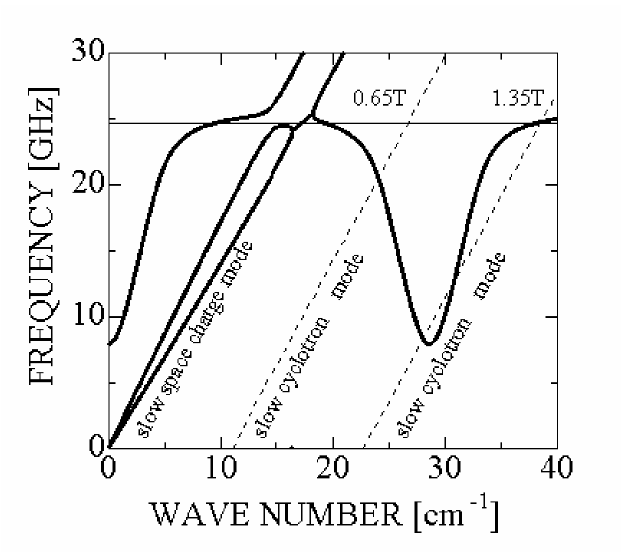

Fig.9 Dispersion curves of fundamental TM_{01} for type B SWS. The beam energy is 30keV.

Acknowledgments

This work was partially supported by a Grant-in-Aid for Scientific Research from Ministry of Education, Science, Sports and Culture of Japan, and partially performed under the Collaborative Research Program between NIFS and University of Tsukuba in cooperation with Japanese universities.

References

[1] K. Ogura et al., IEEJ Trans. FM, **125**, 733(2005).
[2] S. Aoyama et al., Trans. Fusion Sci. Tech. **51**, 325(2007).
[3] O. T. Loza and P. E. Ivanov, *Proc. 13th Int. Conf. High-Power Particle Beams*, Nagaoka, Japan, pp.603-606 (2000).
[4] Kelly Han et al., *IEEE Trans. Plasma Sci*., 30, No.3, June 2002.
[5] P. J. Clarricoats and A. D Olver, *Corrugated Horns for Microwave Antenna* (Peter Peregrinus, London, 1984).
[6] K. Ogura,et at., J. Plasma Phys., 72, 905 (2006).
[7] K. Ogura,et at., Phys. Rev. E, 53, 2726 (1996).
[8] K. Ogura,et at., J. Phys. Soc. Jpn., 67, 3462 (1998).