Experimental Study of Oversized Backward Wave Oscillator with Coaxial Slow-Wave Structure

Hiroyuki YOSHIMURA, Kazuo OGURA, Kiyoshi BANSHO, Hiroshi IIDUKA, Masatoh TAKAHASHI and Akira SUGAWARA

Graduate School of Science and Technology, Niigata University, Niigata 950-2181, Japan

(Received 9 December 2009 / Accepted 31 March 2010)

Studies of coaxial oversized backward wave oscillators (BWOs) are reported. The beam voltage is weakly relativistic (less than 100 kV). The slow-wave structure consists of a periodically corrugated oversized waveguide and periodically corrugated inner conductor, whose target operating frequency due to Cherenkov interaction is in the K-band. A starting energy exists for the coaxial oversized BWO as it does for a hollow oversized BWO. The coaxial slow-wave structure has two surface wave modes caused by the inner and outer corrugations. Operation based on these surface modes can be controlled by the beam diameter. The phase difference between the inner and outer corrugations has little effect on operation of the oversized BWO.

Keywords: oversized backward wave oscillator, weakly relativistic region, periodical corrugation, coaxial slow-wave structure

DOI: 10.1585/pfr.5.S2093

1. Introduction

Moderate- or high-power microwaves are in demand for widespread applications including plasma heating, plasma diagnostics, and radar systems. Slow-wave microwave devices such as backward wave oscillators (BWOs) have been studied extensively as a candidate for high- or moderate-power microwave sources. In slow-wave devices, slow-wave structure (SWS) is used to reduce the phase velocity of electromagnetic waves to the beam velocity. To increase the operating frequency and power-handling capability, oversized devices have been used successfully [1,2]. The term "oversized" means that the diameter D of the SWS is larger than the free-space wavelength λ of the output electromagnetic waves by at least several times.

K- and Q-band oversized BWOs operating in the weakly relativistic region (less than 100 kV) have been reported in Ref. [1], and their improved performance has been reported in Ref. [2]. In these previous experiments, hollow SWSs were used, and manufacturing of the periodical corrugation became difficult as the operating frequency increased. Since introducing a center conductor is expected to increase the operating frequency and stabilize the electron beam propagation, coaxial slow-wave waveguides have been examined for a non-oversized X-band BWO [3, 4]. In this case, the slow-wave is volumetric, having a strong field far from the SWS, and is affected by both the inner and outer SWS. However, the electromagnetic field properties of the oversized SWS are quite different from those of a non-oversized one [5]. The slow-wave becomes a surface wave localized near the SWS, and the surface waves on the inner and outer SWSs are rather isolated. The operation characteristics remain unclear. It is important to examine its operation experimentally on the basis of the surface waves of coaxial oversized SWSs.

In this study, we investigate a coaxial oversized BWO in the K-band. The coaxial SWS is composed of an oversized hollow waveguide and inner conductor. The periodical corrugations are rectangular with the parameters of a K-band BWO [6]. The effects of the inner conductor on operation of coaxial oversized BWO are examined.

2. Coaxial Slow-Wave Structure

The corrugated hollow waveguide and inner conductor that constitute the coaxial SWS are shown in Figs. 1 and 2, respectively. The corrugation parameters of the two cylindrical conductors are the average radius R_0, corrugation amplitude h, periodic length z_0, and corrugation width d. The radius R_0 is the center point between the top and bottom of the corrugations. The corrugation wave number is given by $k_0 = 2\pi/z_0$. The dispersion characteristics of a structure are controlled by varying R_0, h, d, and z_0. The parameters of rectangular corrugation used in this work are listed in Table 1.

Figure 1 shows one modular section including ten periods ($10z_0$). In the experiments, we used hollow oversized SWSs consisting of two modular sections with a total corrugation length of $20z_0$. Figure 2 shows the inner conductors: (a) a straight inner conductor, (b) a corrugated inner conductor, and (c) a corrugated inner conductor with a phase shift $\theta = \pi$. The total lengths of inner corrugation in Figs. 2 (b) and (c) is $20z_0$.

To set the inner conductor at the center of the cylindri-

author's e-mail: f09e105b@mail.cc.niigata-u.ac.jp

cal system, the supports shown in Fig. 3 are placed on the output and input sides of the SWS. The support on the right in Fig. 3 is the input support frame and acts as a beam limiter. The limiter's outer radius and inner radius are ϕ28 mm and ϕ19 mm, respectively.

Table 1 Parameters of rectangular corrugation.

	R_0 [mm]	h [mm]	z_0 [mm]	d/z_0 [%]
Outer corrugation	15.1	1.1	3	50
Inner corrugation	8.4	1.1	3	50

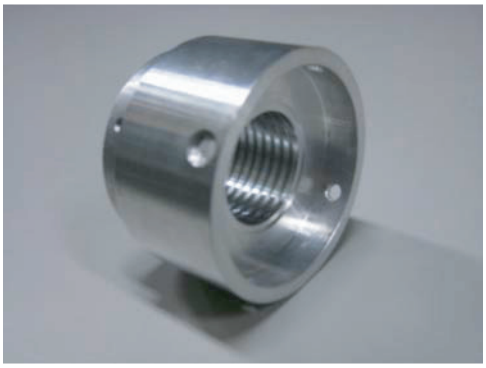

Fig. 1 One modular section of the hollow oversized SWS.

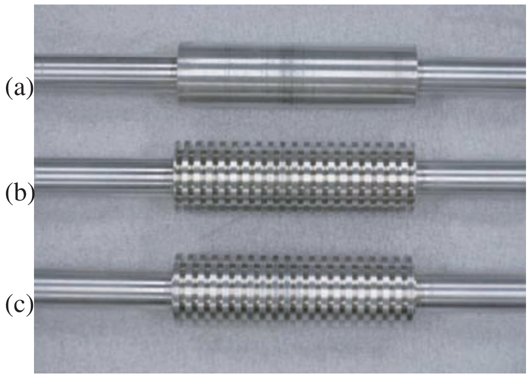

Fig. 2 Inner conductors used in the SWS.

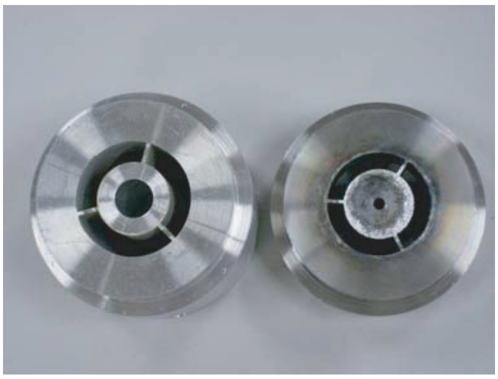

Fig. 3 Inner conductor supports.

Three types of coaxial SWS are tested: Type A, composed of an hollow oversized SWS and the straight inner conductor shown in Fig. 2 (a); Type B, composed of an hollow oversized SWS and the corrugated inner conductor shown in Fig. 2 (b); and Type C, composed of an hollow oversized SWS and the corrugated inner conductor shown in Fig. 2 (c). The phase difference between the inner and outer corrugations is $\theta = 0$ for Type B and $\theta = \pi$ for Type C.

3. Electron Beam

It is very difficult to generate a uniformly distributed annular beam using a cold cathode, especially in the weakly relativistic region. To obtain an annular electron beam, we use hollow cathodes with velvet on the axisymmetric emitting edge. The diameter of the electron beam is varied using cathodes of different diameters. The beam quality is observed by the burn patterns in thermally sensitive paper.

Figures 4 and 5 show the burn patterns of the electron beam. The patterns are the result of a five-shot overlay at about 80 kV. For a hollow cathode of diameter ϕ20 mm, the burn pattern is an annulus when the beam limiter without the support is used. In contrast, the burn pattern is not an annulus for the beam limiter with the support. The support frame of the inner conductor affects the electron beam injection. For a hollow cathode of diameter ϕ28 mm, the burn pattern is an annulus with both beam limiters (without

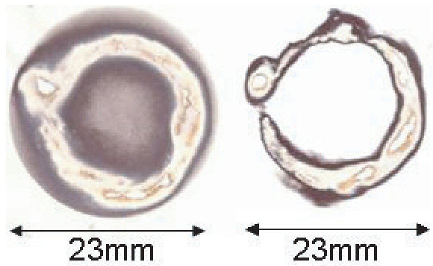

Fig. 4 Burn patterns of electron beam for a hollow cathode of diameter ϕ20 mm. Left and right sides are without and with the support frame, respectively.

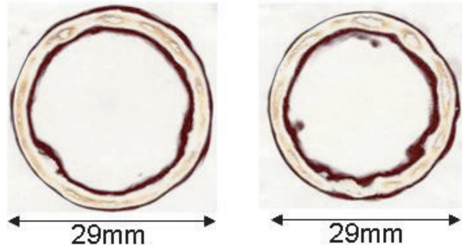

Fig. 5 Burn patterns of electron beam for a hollow cathode of diameter ϕ28 mm. Left and right sides are without and with the support frame, respectively.

and with the support). The support has little effect when the ϕ28 hollow cathode is used.

4. Coaxial Oversized BWO Experiment

The experimental setup for the coaxial oversized BWO is shown schematically shown in Fig. 6. An output voltage of up to 100 kV from the pulse-forming line is applied to the cold cathode. A uniform axial magnetic field B_0 for beam propagation is provided by 10 solenoid coils. The value of B_0 can be changed from zero to about 1 T. The microwave outputs are picked up by a rectangular horn antenna typically located 600 mm from the output window.

For oversized BWOs using a hollow SWS, it has been shown theoretically and experimentally that a critical beam energy exists (the so-called starting energy) at which meaningful radiations begins to oscillate [1, 7]. In Fig. 7, the microwave power of the oversized BWO is plotted as a function of the beam voltage for the Type C coaxial SWS. The beams are generated by two cathodes of diameter ϕ20 and ϕ28 mm with beam limiters having outer and inner diameters of ϕ28 and ϕ19 mm, respectively. Hence, beams propagate near the inner corrugation for the ϕ20 cathode and near the outer corrugation for the ϕ28 cathode. For both cathodes, radiation is detected above about 50 kV. Figure 7 shows that a starting energy exists for the coaxial oversized BWO, as it does for the hollow oversized BWO.

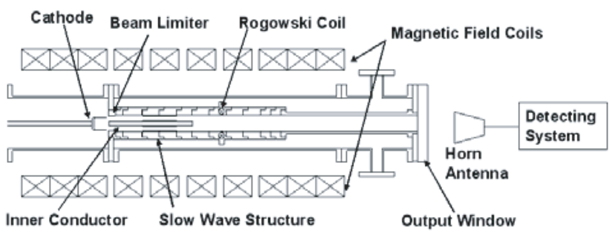

Fig. 6 Schematic diagram of the experimental setup.

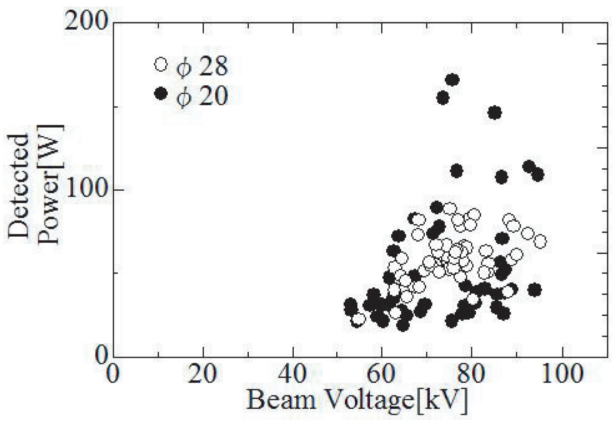

Fig. 7 Output power versus cathode voltage. Coaxial SWS is Type C. Cathode diameter is ϕ28 mm (open circles) and ϕ20 mm (solid circles). Magnetic field is 0.8 T.

Data are also taken for Type B, and the same starting energy as Type C is obtained with both the ϕ20 and ϕ28 cathodes. Types B and C coaxial SWSs are composed of a hollow oversized SWS and a corrugated inner conductor. The only difference between them is the relative phase θ between the inner and outer corrugations: $\theta = 0$ for Type B and $\theta = \pi$ for Type C. The relative phase of the corrugations does not affect the starting energy.

For a Type A coaxial SWS, the starting energy and power level are almost the same as in Fig. 7 if the ϕ28 cathode is used. However, no microwave power is detected when the ϕ20 cathode is used.

Figure 8 shows an example of the detected signals at energies above the starting energy. The beam voltage and current are about 70 kV and 100 A, respectively, at the time of the microwave peak. The microwave signal is split into two branches. One consists of a short waveguide and forms a prompt signal. The other is a delay line and forms a delayed signal. In Fig. 8, the operating frequency estimated from the delay time is about 26 GHz. The estimated error of this frequency measurement is around ± 1–2 GHz.

We examine how the operating frequency depends on the beam radius by using cathodes of diameter ϕ20 and ϕ28 mm. The measured frequencies are plotted in Fig. 9 (a) for Type B and Fig. 9 (b) for Type C.

In Fig. 9 (b), the frequencies are mostly distributed from 22 to 24 GHz for the ϕ20 cathode and from 25 to 29 GHz for the ϕ28 cathode. Although the data scatter is fairly large, it can be concluded that the operating frequency increases with increasing cathode radius. In other words, the frequency is around 23 GHz if beams propagate near the inner corrugation and around 27 GHz if they propagate near the outer corrugation. Operating frequencies are also measured for a Type B coaxial SWS: almost the same dependence of the frequency on the beam radius is obtained, as shown in Fig. 9 (a).

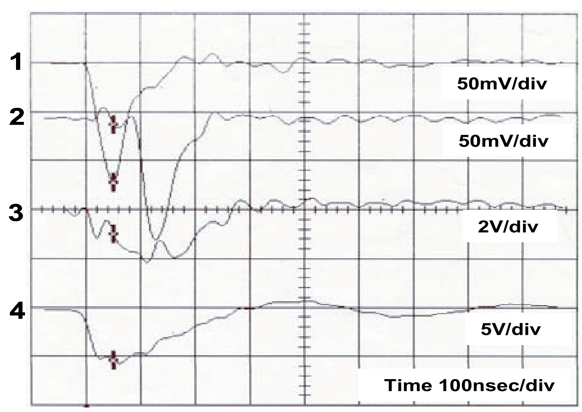

Fig. 8 Waveform of measured signals. 1: prompt signal, 2: delayed signal, 3: beam current, and 4: beam voltage.

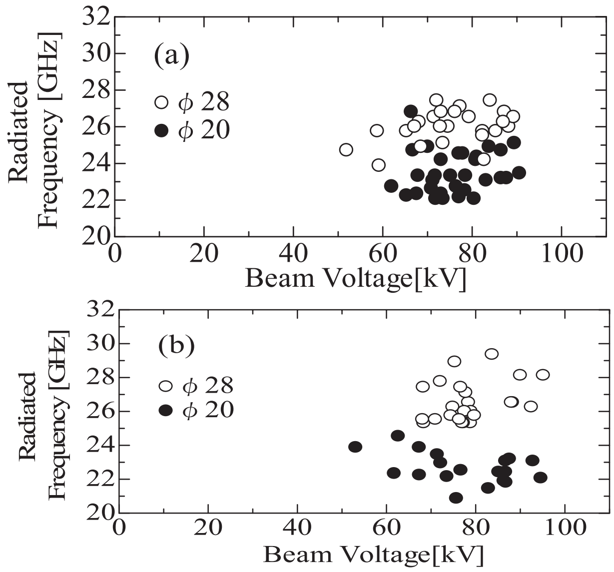

Fig. 9 Frequency versus voltage. Coaxial SWS is (a) Type B and (b) Type C. Cathode diameter is ϕ28 mm (open circles) and ϕ20 mm (solid circles). Magnetic field is 0.8 T.

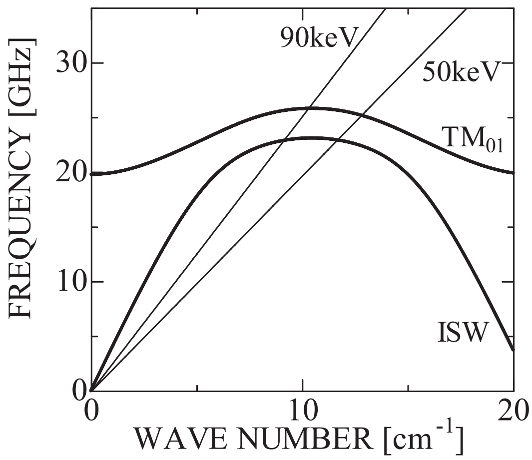

Fig. 10 Dispersion curves of Type B SWS with $\theta = 0$. Diameter of electron beam is ϕ27 mm. Beam lines of 50 and 90 keV are also plotted.

5. Discussion and Conclusion

For an oversized SWS, the interaction between the beam and the slow-wave occurs well below the light line. Slow-waves are evanescent waves, i.e., surface waves of the corrugation. They decrease sharply from the SWS wall. For effective beam coupling to the electromagnetic field, the beam should propagate within a few mm of the wall [5].

Figure 10 shows the dispersion curves of a Type B SWS. The dispersion curves of Type C are very close to those of Type B, and the two overlap. For Types B and C, the inner conductor has a surface wave near its corrugation. This inner surface wave is labeled "ISW" in Fig. 10. The TM_{01} mode in Fig. 10 is an upper mode and is attributed to the outer corrugation. The TM_{01} mode is also a surface wave.

When the ϕ20-mm-diameter cathode is used, electron beams pass near the inner conductor, away from the outer conductor. For Type A, no meaningful output power is observed in this case. In contrast, radiation is observed for of Types B and C. This radiation is considered to be generated by the beam's interaction with the ISW. Radiation occurring with the ϕ28 cathode in Fig. 10 is due to the TM mode, because the beams propagate near the outer corrugation and away from the inner corrugation. Radiation with the ϕ28 cathode is observed for Types A, B, and C, in which the outer corrugation has the TM mode. The oscillation frequencies are about 23 GHz for the ISW and 26 GHz for the TM mode, which agree fairly well with the experimental values.

In conclusion, we studied coaxial oversized BWO operation. A starting energy exists for the coaxial oversized BWO, as it does for a hollow oversized BWO. Microwave oscillations are generated by the ISW of the inner corrugation or the TM mode of the outer corrugation. The operation of the ISW and TM modes can be controlled by varying the beam diameter. The phase difference between the inner and outer corrugations has no obvious effect. Although the increase in frequency and stabilization of beam propagation by the center conductor are unclear in the present work, frequency changes with changing beam radius are newly demonstrated. This frequency tunability is unique and may be of considerable interest for practical use.

Acknowledgments

This work was partially supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture of Japan, and by the NIFS Collaboration Research Program.

[1] K. Ogura *et al.*, IEEJ Trans. FM. **127**, 733 (2005).
[2] S. Aoyama *et al.*, Fusion Sci. Tech. **51**, 325 (2007).
[3] X. Zheng *et al.*, J. Phy. Soc. Jpn. **64**, 1402 (1995).
[4] G. Liu *et al.*, J. Appl. Phys. **103**, 093303 (2008).
[5] H. Yamazaki *et al.*, J. Plasma Phys. **72**, 915 (2006).
[6] K. Ogura *et al.*, IEEJ Trans. FM. **127**, 681 (2007).
[7] K. Minami *et al.*, IEEE Trans. Plasma Sci. **23**, 124 (1995).