Weakly Relativistic K-Band Oversized Backward Wave Oscillator with Bragg Reflector at Beam Entrance of Slow Wave Structure

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(Received 4 December 2006 / Accepted 26 February 2007)

We report an oversized K-band backward wave oscillator (BWO) operating above 20 GHz in the weakly relativistic region less than 100 kV. It is very important to prevent microwave from going into the beam diode, since intense microwaves will harmfully affect beam generation. A weakly relativistic oversized BWO is demonstrated using a Bragg reflector at the beam entrance of slow wave structure (SWS). The effect of the Bragg reflector on the BWO operation is examined, by changing the boundary condition at the beam entrance. The Bragg reflector improves the performance of the oversized BWO.

Keywords: oversized backward wave oscillator, periodic slow wave structure, weakly relativistic electron beam, K-band, Bragg reflector

DOI: 10.1585/pfr.2.S1041

1. Introduction

Microwaves at moderate-power level or high-power level are demanded for widespread applications such as plasma heating, plasma diagnostics, telecommunication systems and radar systems. 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 power microwave sources [1]. In the slow-wave devices, a slow-wave structure (SWS) is used to reduce the phase velocity of electromagnetic wave to the beam velocity. To increase the power handling capability and/or the operating frequency, oversized SWSs have been used successfully [2–8]. The term "oversized" means that the diameter is larger than free-space wavelength λ of output electromagnetic wave by several times or more. The relativistic diffraction generator and multi-wave Cherenkov generator are special versions of the oversized BWO and have produced peak powers of GW level [2, 3]. For these relativistic devices, the pulsed power and magnetic field systems are very large and heavy. For practical applications, operations at reduced voltage and at reduced magnetic field are preferable, since the systems become compact. However, the phase velocity of electromagnetic mode should be slowed down close to the beam velocity, ensuring enough beam coupling with electromagnetic modes. This issue becomes very difficult by reducing the beam voltage. In Ref. 6, the power level about 500 MW has been demonstrated at 8.3 GHz (X-band) at a moderate voltage of about 500 kV.

We study oversized BWOs operating in the relatively high frequency region, in K-band and Q-band [4, 5, 7, 8]. Unique features of our BWOs are (1) they are driven by a weakly relativistic electron beam less than 100 kV, (2) the operation frequencies are relatively high, above 10 GHz and (3) the guiding magnetic field is relatively low, less than 1 T. Note that high-power operations beyond 10 GHz are difficult for the conventional non-oversized slow-wave devices. Recently, the performance of weakly relativistic oversized BWO has been improved. Radiation powers up to 500 kW (K-band) and up to 200 kW (Q-band) have been demonstrated in reference [9]. The quality factor Pf^2 of the weakly relativistic BWO has been improved up to about $3.5{\times}10^5$ kW·GHz^2.

Since beam generation will be harmfully affected by such intense microwaves, it is very important to prevent microwave from going into the beam diode region. In non-oversized devices, the beam entrance of SWS can be terminated to a cut-off neck in order to reflect the microwave. For the oversized BWO, the electromagnetic field concentrates in the vicinity of SWS wall and the electron beam should be propagated within a few mm from the wall keeping its annular shape. The beam radius after cut-off neck becomes too small to operate efficiently. Other reflector than cut-off neck is required. A reflector such as mesh or inner metal plate at the beam entrance section is used to reflect microwaves [4–9].

Beam interactions with such obstacles might generate plasma and cause a serious problem, so-called pulse shortening. Currently, this issue becomes very important problem and is studied extensively, see for example Chapter 4 of reference [1]. Moreover, obstacles at the entrance may reduce the beam quality. By introducing beam energy spread and some non-uniformity of beam, the performance of the oversized BWO may be deteriorated. It is preferable

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to remove any obstacle from the beam path.

This work is aimed at studying a weakly relativistic oversized BWO with a Bragg reflector at the beam entrance of SWS. The Bragg reflector reflects microwaves, while it is open for beam propagations. By changing the boundary condition at the beam entrance, the effect of the Bragg reflector on the BWO performance is examined.

2. Oversized K-Band BWO with a Bragg Reflector

We use cylindrical SWS, corrugated periodically as shown in Fig. 1. Dispersion characteristics of SWS are determined by average radius R_0, corrugation amplitude h and periodic length z_0. The corrugation wave number is given by $k_0 = 2\pi/z_0$. The dispersion characteristics of the structure are controlled by changing R_0, h and z_0. Parameters of two kinds of SWS are listed in table 1. And the dispersion curves of the lowest axisymmetric transverse magnetic (TM_{01}) mode are shown in Fig. 3. The oscillation between f_A and f_B in 25.5 GHz-SWS will not pass through 22 GHz-SWS. Oversized K-band BWO with a Bragg reflector is composed of these SWSs, as Fig. 3.

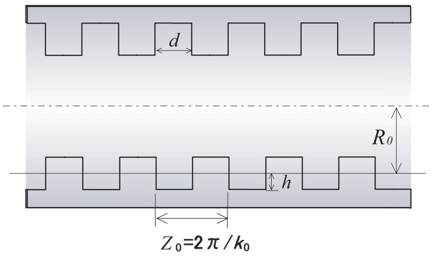

Fig. 1 Periodically corrugated cylindrical SWS.

Table 1 Parameters of oversized SWS.

	R_0 [mm]	h [mm]	z_0 [mm]	$2R_0/\lambda$
22 GHz-SWS	15.3	1.3	3.4	2.2
25.5 GHz-SWS	15.1	1.1	3.0	2.6

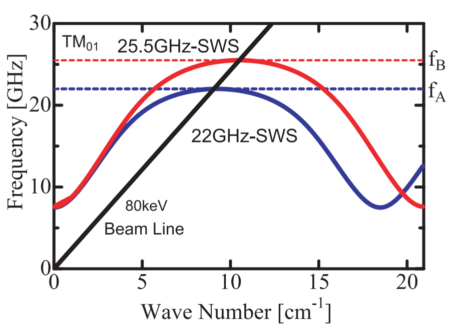

Fig. 2 Dispersion curves of TM_{01} for periodic SWS listed in table 1. One has the upper cut-off frequency of f_A = 22 GHz and the other has f_B = 25.5 GHz.

The 22 GHz-SWS having length L_1 is placed at the beam entrance as a Bragg reflector. After smooth waveguide with L_2, 25.5 GHz-SWS with length L_3 is connected for microwave generations. We choose $L_2 = 10z_0$ and $L_3 = 20z_0$, based on the consideration below.

There exist two threshold conditions for the oscillation in the SWS, i.e., the starting current and the starting energy [7, 10]. In order to satisfy the latter condition, the interaction width Δk_z in the wave number space should be larger than $2\pi/L$. Here, L is the length of SWS. In the oversized SWS, this condition becomes critical and cannot be satisfied by increasing only the beam current. Figure 4 shows how Δk_z change with increasing beam energy for the 22 GHz-SWS. By increasing beam energy and approaching the beam interaction point to the π point, the width Δk_z increases. At a critical beam energy (so-called starting energy), Δk_z becomes broad enough to satisfy the oscillation condition. Oscillations will not start for 22 GHz-SWS with $L_1 = 10z_0$, and it may work as a microwave reflector. For 25.5 GHz-SWS, the similar curve as Fig. 4 is obtained and it is predicted that the oscillation will start about 50-60 kV if $L_3 = 20z_0$. For the smooth waveguide, L_2 is optimized experimentally as presented below.

3. Experiment

Output voltage up to about 100 kV from the pulse-forming line is applied to a cold cathode. A hollow cold

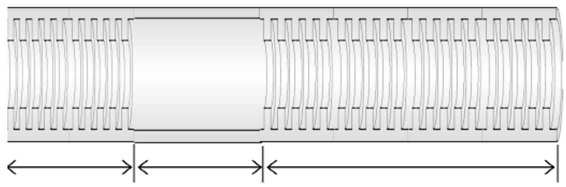

Fig. 3 Schematic of oversized BWO with a Bragg reflector.

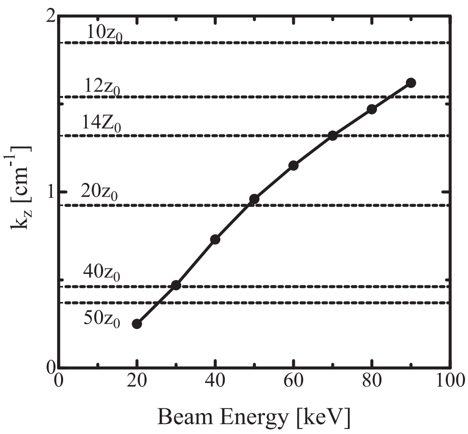

Fig. 4 Numerically obtained interaction width Δk_z versus beam energy. Horizontal dashed lines are $2\pi/L$ for the SWS length L from $10z_0$ to $50z_0$.

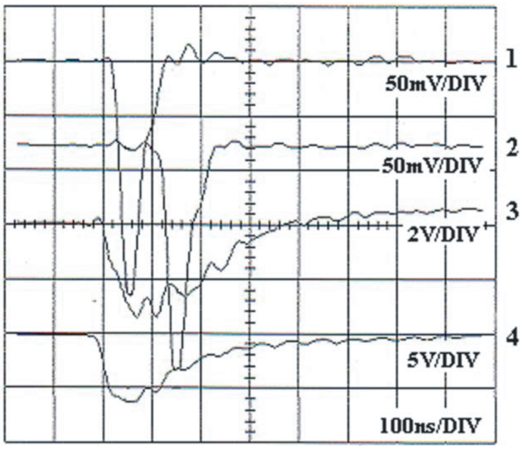

Fig. 5 Waveforms of measured signal:1 prompt signal, 2 delayed signal, 3 beam current and 4 beam voltage.

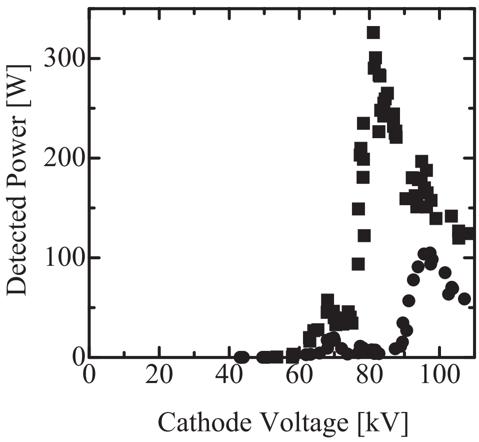

Fig. 6 Power versus the cathode voltage: (■) for BWO with the Bragg reflector and (•) for BWO without the Bragg reflector.

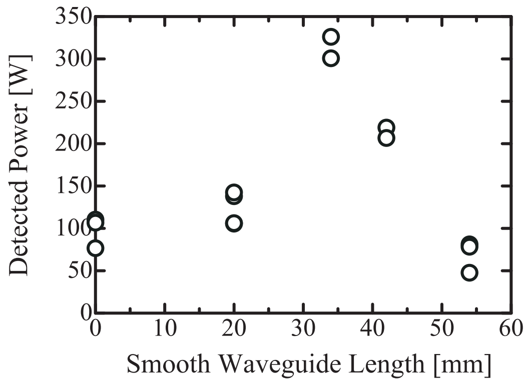

Fig. 7 Power dependence of the BWO with the Bragg reflector on the smooth waveguide length.

cathode with velvet on the emitting edge is used. Uniform magnetic field B_0 is applied. The maximum value of B_0 is about 1 T. Injected electron beam has an annular shape, which is examined by observing burn patterns in thermally sensitive paper obtained by intersecting the beam. The outer radius of beam is adjusted by the cathode diameter and the beam limiter. The thickness of annular is adjusted by changing the width of velvet and is typically 2-3 mm.

The microwave output is picked up by a rectangular horn antenna located away from the output window. In Fig. 5, an example of detected signals is shown. The beam voltage and current are respectively about 81 kV and 320 A, at 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. The delay time is 97 nsec, from which the radiation frequency is estimated to be 26 GHz. The observed frequencies are well consistent with the frequencies of crossing points between the beam line and the fundamental TM_{01} of 25.5 GHz-SWS.

Figure 6 shows the dependence of the detected microwave power on the beam voltage. The squares ■ are obtained with 22 GHz-SWS ($L_1 = 10z_0$) and 25.5 GHz-SWS ($L_3 = 20z_0$). The length of smooth waveguide is $L_2 = 34$ mm, which is determined from the experimental results in Fig. 7. Figure 7 shows that there exists an optimal value of L_2 (= 34 mm).

The weakly relativistic oversized BWO with Bragg reflector in Fig. 6 generates meaningful radiations above the starting energy for the 25.5 GHz-SWS. The output power has some peaks. These peaks may correspond to an axial mode of the SWS cavity. And the axial mode changes by changing the beam voltage. By increasing the beam voltage, the interacting point between the beam and electromagnetic wave is shifted to the point of $k_z z_0 = \pi$.

The circles • are obtained merely replacing 22 GHz-SWS ($L_1 = 10z_0$) to a smooth waveguide having the same length. The others do no change from those for ■. The power level decreases by a factor of 3. The power peak corresponding to the axial mode is shifted due to the change of the SWS end condition. It is clearly demonstrated that the performance of oversized BWO is improved by the Bragg reflector.

The effects of the SWS end are examined. In Fig. 8, 22 GHz-SWS is replaced by 25.5 GHz-SWS or cupper mesh. For the 25.5 GHz-SWS with ten periods, i.e., $L_1 = 10z_0$, output power level and peak of power are the same as those without the Bragg reflector in Fig. 6. This means that the microwave reflection between f_A and f_B (Fig. 2) is essential for the power increase in Fig. 6. When mesh is used, the power levels are below 50 W, and less than those for the open ends. Due to the mesh, the beam current decreases to about 70 % and the beam quality may deteriorate. The mesh position affects the axial mode and shifts the power peak.

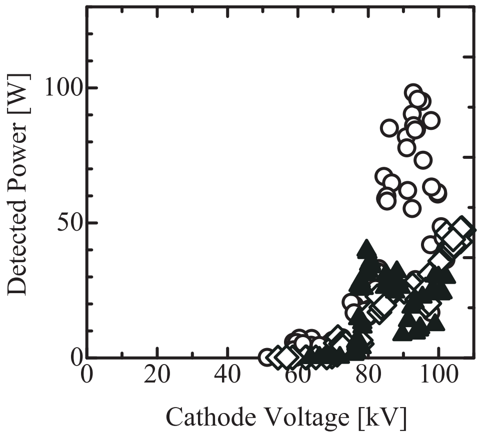

Fig. 8 Power of oversized BWO versus the cathode voltage. Beam entrance is the 25.5 GHz-SWS (○), 34 mm smooth waveguide terminated by mesh (▲) and 68 mm smooth waveguide terminated by mesh (◇).

4. Discussion and Conclusion

Oversized SWS can be used as a Bragg reflector, instead of mesh. Due to the change of end conditions, electromagnetic properties may be changed. The wave-beam interaction will be affected, since it depends on the field properties. In references [10, 11], the effect of SWS end conditions on the non-oversized BWO operation has been studied. It has been shown that the electromagnetic field properties and the quality factors of axial mode are strongly affected by the end conditions. The efficiency and frequency agility of the non-oversized BWO can be improved by changing the end conditions [12, 13]. However, the discussions are restricted in non-oversized BWOs, in which the electromagnetic fields are volumetric. In the case of oversized BWO, the field properties are quite different [6–9]. We show that the end conditions affect the BWO performance, even in the oversized case. And the oversized SWS can improve the performance of oversized BWO compared with the mesh reflector. The weakly relativistic oversized BWO with Bragg reflector at the beam entrance of SWS is of considerable interest for practical use. In order to realize more efficient and stable oversized BWO using Bragg reflectors, the field properties of operation mode and the beam coupling in the oversized SWS should be studied more definitely, considering realistic boundary conditions.

Acknowledgments

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

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