Studies of a Weakly Relativistic Oversized Backward Wave Oscillator with Disk Cathode and Rectangular Corrugation

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Keywords : oversized backward wave oscillator, weakly relativistic, disk cathode, annular electron beam, rectangular corrugation

An oversized BWO with a novel cathode and a rectangular corrugation is studied. The beam voltage is weakly relativistic, less than 100 kV. For high-power microwave sources operating in relativistic regions, high-current relativistic electron beams are obtained by using cold cathodes, with the help of explosive emission. It is very difficult to realize a uniform electron beam. The cathode plays a very important role and has been studied extensively. To increase the azimuthal uniformity, the annular cathode surface needs to be modified, for example, coatings with velvet, carbon fiber or a mixture of fine graphite powder and epoxy. As the cathode voltage becomes lower, the uniform electron emission becomes the much more serious problem. To the best of our knowledge, velvet cathode is only one, which has been successfully used to generate uniform annular beam in the weakly relativistic. Velvet cathode can be used with the low-electric field, in return for the low-repetition rate and the short lifetime. For practical devices, it is necessary to develop a new cathode with a high-repletion and long lifetime, which can generate the uniform beam with a high current density even in the weakly relativistic region.

Sinusoidally corrugated periodic waveguides have been used in many high-power BWO experiments, since the electric fields become strong for high-power operations. For rectangularly corrugated SWSs, there exist strong electric fields near the sharp edges. The electric fields become unacceptably strong if used in high-power operations at power level above some hundreds of MW. However, for moderate power level of a few MW or less, the rectangular shape may be better than the sinusoidal shape, since it provides enough slowing of wave and adequate beam coupling.

This work is aimed at studying a weakly relativistic oversized BWO with a new cold cathode. The beam voltage is weakly relativistic, less than 100 kV. The beam current is up to about 500 A.

Fig. 1. Output radiation of oversized BWO versus the cathode voltage

We propose to use a novel disk cathode, in order to get a uniformly distributed annular electron beam. The novel disk cathode is successfully used even in the weakly relativistic region. This cold cathode is made of metal only and is a unique explosive cathode. By injecting the annular electron beam by the disk cathode, a weakly relativistic oversized BWO consisting of rectangularly corrugated cylindrical waveguide is demonstrated. The oscillation starting energy is about 60 kV for a 10-period rectangular corrugation. As shown in Fig.1, the output power increases with increasing the beam voltage. The estimated output power reaches at about 200 kW.

The mode control of the oversized BWO is a serious issue to be solved. The mode control between axisymmetric and nonaxisymmetric modes is performed by changing the end condition of BWO. The weakly relativistic oversized BWO mentioned above is unique and of considerable interest for practical use.

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Studies of an oversized BWO with a novel cathode and a rectangular corrugation are presented. The beam voltage is weakly relativistic, less than 100 kV. We propose to use a disk cathode made of metal only. The disk cathode can generate a uniformly distributed annular electron beam even in the weakly relativistic case. By using the annular electron beam, a weakly relativistic oversized BWO consisting of rectangularly corrugated cylindrical waveguide is demonstrated. The oscillation starting energy is about 60 kV for a 10-period rectangular corrugation. The maximum output power is estimated about 200 kW. The operation mode between axisymmetric and nonaxisymmetric modes can be controlled by changing the end condition of BWO.

Keywords : oversized backward wave oscillator, weakly relativistic, disk cathode, annular electron beam, rectangular corrugation

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⁾⁻⁽⁹⁾. 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.(5), the power level about 500 MW has been demonstrated at 8.3 GHz (X-band) at a moderate voltage of about 500 kV.

In Refs.(4) and (6)-(9), we have been studying oversized BWOs operating in the relatively high frequency region, in K-band and Q-band. 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 about 500 kW (K-band) and up to about 200 kW (Q-band) have been demonstrated in Ref.(8).

For high-power microwave sources operating in relativistic regions (above a few hundred kV), high-current relativistic electron beams are obtained by using cold cathodes, with the help of explosive emission. It is very difficult to realize a uniform electron beam. The cathode plays a very important role and has been studied extensively, see for example Chapter 9 of Ref.(1). To increase the azimuthal uniformity, the annular cathode surface needs to be modified, for example, coatings with velvet, carbon fiber or a mixture of fine graphite powder and epoxy. As the cathode voltage becomes lower, the uniform electron emission becomes the much more serious problem. To the best of our knowledge, velvet cathode is only one, which has been successfully used to generate uniform annular beam in the weakly relativistic BWO⁽⁴⁾⁽⁶⁾⁻⁽⁹⁾. Velvet cathode can be used with the low-electric field, in return for the low-repetition rate and the short lifetime. For practical devices, it is necessary to develop a new cathode with a high-repletion and long lifetime, which can generate the uniform beam with a high current density even in the weakly relativistic region.

Periodic structures are widely used in modern science and technology such as optics, acoustic design, infrared spectroscopy and microwave technology⁽¹⁰⁾. Sinusoidally corrugated periodic waveguides have been used in many high-power BWO experiments, since the electric fields become strong for high-power operations. For rectangularly corrugated SWSs, there

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exist strong electric fields near the sharp edges. The electric fields become unacceptably strong if used in high-power operations at power level above some hundreds of MW⁽⁵⁾. However, for moderate power level of a few MW or less, the rectangular shape may be better than the sinusoidal shape, since it provides enough slowing of wave and adequate beam coupling.

This work is aimed at studying a weakly relativistic oversized BWO with a new cold cathode. We propose to use a novel disk cathode shown in Fig.1(a), in order to get a uniformly distributed annular electron beam. The idea of disk cathode was presented in Ref.(11), in order to generate a long-pulse, intense relativistic electron beam. In Ref.(12), the disk cathode was used to avoid the pulse shortening in a non-oversized relativistic BWO and to study a long-pulse operation. In this paper, it is demonstrated that the novel disk cathode is successfully used even in the weakly relativistic region. This cold cathode is made of metal only and is a unique explosive cathode. By injecting the annular electron beam by the disk cathode, a weakly relativistic oversized BWO consisting of rectangularly corrugated cylindrical waveguide is demonstrated. Starting energy and operation mode of the oversized BWO are examined experimentally.

2. Cold Cathode

We use a cold cathode to obtain a beam with a high current density in the range of 100 A/cm² or more. It is very difficult to generate a uniformly distributed annular beam by the cold cathode, especially in the weakly relativistic region. In the weakly relativistic BWO, cathode voltage is less than 100 kV. The average electric field between the cathode and anode is about 10⁵/cm or less. In the past, we have used a hollow cathode with velvet on the axisymmetric emitting edge, in order to obtain an annular electron beam, see Fig.1(b) and Fig.2(b). The velvet cathode is the only cold cathode which operates properly in the weakly relativistic region, as in Refs.(4) and (6)-(9). The beam shape is observed by the burn patterns in thermally sensitive paper. By controlling velvet, the quality of beam by the hollow cathode is improved. A relatively uniform annular shape is realized as shown in Fig.3. The average radius of annular is nearly the same as the cathode diameter.

We propose to use a novel disk cathode in the weakly relativistic region less than 100 kV. The idea of disk cathode was presented by Loza et al.⁽¹¹⁾, and used in the relativistic cases. In this paper, the novel cathode as shown in Fig.1(a) and 2(a) is tested in the weakly relativistic region. The burn patterns are shown in Fig.3. For a hollow cathode, the diameters of cathode and beam limiter are 23 mm and 26 mm, respectively. For a disk cathode, the diameters of cathode and beam limiter are 25 mm and 28 mm, respectively. The beam generated by the disk cathode has the more uniform distribution and has the higher current density compared with the hollow cathode with velvet. Note that any coating on the disk cathode surface is not required. This is a surprising result. It is clear that the disk cathode is suitable for the weakly relativistic case as well as the relativistic case. As can be seen from Fig.1, the novel disk cathode is expected to reduce the unwanted plasma produced at the cathode and paves the way for long-pulse high-power microwave sources.

3. Rectangular SWS

Cylindrical SWS is corrugated periodically as shown in Fig.4. Dispersion characteristics of SWS are determined by average

Fig. 1. Cross sections of (a) disk cathode and (b) hollow cathode

Fig. 2. Photographs of (a) disk cathode and (b) hollow cathode. The disk cathode is made of copper; The hollow cathode is made of aluminum with velvet on the edge

Fig. 3. The burn patterns of annular electron beam. Left-side is for a hollow cathode with velvet obtained from five-shot overlay at about 90 kV; Right-side is for a novel disk cathode obtained from one-shot at about 80 kV

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 the structure are controlled by changing R_0 , h , d and z_0 . Parameters of rectangular SWS are listed in Table 1. We also list parameters of sinusoidal

Fig. 4. Schematic diagram of rectangularly corrugated SWS

Table 1. Parameters of Periodically Corrugated SWS

	R_0 [mm]	h [mm]	d [mm]	z_0 [mm]
Rectangular SWS	15.1	1.1	1.5	3.0
Sinusoidal SWS	15.6	1.65	---	3.0

corrugation having almost the same dispersion characteristics as the rectangular SWS.

To analyze electromagnetic field properties of periodic system, various methods including the Rayleigh method and the field matching method have been developed⁽¹⁰⁾. The Rayleigh method is based on the Rayleigh hypothesis, which assumes that the fields inside the periodic corrugation are also expressed by the same spatial harmonic series as outside the corrugation. The shortcoming of the method is that it is difficult to obtain exact results in case of the deep corrugation. Theoretical limit for its applicability has been proposed and argued extensively. For the field matching method, there is no such limitation. In the field matching method, the field inside corrugation is expressed by appropriate functions so as to satisfy the boundary conditions at the wall of rectangular corrugation. Then, the functions inside corrugation are matched to the periodic functions outside corrugation, by using the boundary conditions at the boundary surface between the inside and outside the corrugation. The Rayleigh method is particularly simple and important for self-consistent analyses⁽¹³⁾⁻⁽¹⁵⁾. The method is suitable for analyses of sinusoidally corrugated SWS, which is used in many high-power BWO experiments. For the rectangular corrugation, the field properties are obtained by the field matching method. The dispersion curves of the lowest axisymmetric transverse magnetic (TM_{01}) mode are shown in Fig.5. The growth rate for the rectangular SWS is higher than that of the sinusoidal SWS. The rectangular shape provides strong beam coupling. It is better than the sinusoidal shape. As compared with the sinusoidal shape, the rectangular shape is easier to manufacture and the manufacture accuracy is better. Hence, the dispersion characteristics are controlled more easily and accurately.

As is discussed in Ref.(6), there exist two threshold conditions for the oscillation in the SWS, i.e., the starting current and the starting energy. 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 6 shows how Δk_z change with increasing beam energy. 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 up to 80 kV for sinusoidal SWS with $L =$

Fig. 5. Dispersion curves of fundamental TM_{01} for periodic SWS listed in Table 1; Thick line is for the rectangular SWS and thin line for the sinusoidal SWS Fig. 6. 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 $50z_0$

$10z_0$. For the rectangular SWS with $L = 10z_0$, it is predicted that the oscillation will start about 58 kV. For the sinusoidal SWS, the beam coupling becomes weak and the starting energy becomes higher compared with the rectangular case.

4. Oversized BWO Experiment

Experimental setup is schematically shown in Fig.7. Output voltage up to about 100 kV from the pulse-forming line is applied to a cold cathode. A hollow cold 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. The microwave output is picked up by a rectangular horn antenna located away from the output window.

In Fig. 8, an example of detected signal is shown. The beam voltage and current are respectively about 98 kV and 470 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 after about 31 m delay line is 152 nsec, from which the radiation frequency is estimated to be 26 GHz. The observed frequencies are fairly consistent with the frequencies of crossing points between the beam line and the fundamental TM_{01} of SWS.

There exist other fundamental modes such as nonaxisymmetric

Fig. 7. Schematic diagram of experimental setup for the oversized BWO

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

Fig. 9. Radiation patterns with the straight cylinder length of (a) 66 mm and (b) 100 mm; Dashed curves are theoretical curves of (a) TM_{01} and (b) HE_{11} mode, respectively; The beam voltage is in the range of 85-100 kV and error bar expresses scattering of data at each angle

hybrid HE_{11} and HE_{21} modes⁽⁷⁾⁽⁹⁾, very close to the fundamental TM_{01} . The operation mode cannot be determined uniquely by the frequency measurement only. To examine the mode, the radiation patterns are measured as shown in Fig.9, by changing the detection angle in an equatorial plane around a pivot at the center of output window. The operation mode changes by the straight cylinder length before SWS in Fig.7. For a 66 mm length straight cylinder, the dominant radiation mode is TM_{01} mode as Fig.9(a). By increasing the length to 100 mm, the radiation mode becomes

Fig. 10. Output radiation of oversized BWO versus the cathode voltage

HE_{11} mode as Fig.9(b). This mode predominantly consists of nonaxisymmetric transverse electric TE_{11} component and is characterized by a peak at the center. For the longer cylinder than 100 mm, TM_{01} mode becomes dominant again. Both axisymmetric and nonaxisymmetric modes are observed and are controlled by the axial condition, i.e., the input cylinder length.

Figure 10 shows the dependence of the detected microwave power on the beam voltage. The operation mode is the fundamental TM_{01} mode. The weakly relativistic oversized BWO generates meaningful radiations above the starting energy for the rectangular SWS. Some peaks can be seen and may correspond to axial modes of the SWS cavity. The operating 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 maximum power is estimated to be about 200 kW.

5. Discussion and Summary

In the relativistic high-power microwave devices, high-current electron beam are generated based on the explosive emission. In the explosive emission, plasma is generated on the cathode surface and acts as electron emitter. The cathode plasma expansion will close the cathode-anode gap and terminate the electron beam. This results in the microwave pulse shortening. For the hollow cathode, a large amount of unwanted plasma might be formed along the cathode surface as in Fig.1(b). A way of overcome this problem is disk cathode, as presented in Ref.(11). A disk cathode reduces the amount of unwanted plasma. It was also reported that the angular spectrum of electrons is small enough to apply high-power microwave devices. The disk cathode is a promising candidate for a useful long-pulse explosive cathode. However, it was considered for the relativistic devices and the operation in the weakly relativistic region was not expected. In this paper, we demonstrate that an explosive cathode made of metal only can be available even for the weakly relativistic case. Material such as aluminum, copper and stainless steel are tested as cathode. Up to now, the best result is obtained by a copper cathode. It is also expected that shape of emitting edge and surface condition have a strong effect on the performance. More definite study on the emission mechanism should be made in the future.

In the high-power operation of the oversized BWO, the beam interaction with the nonaxisymmetric mode is the same as the axisymmetric interaction. For the high-power operation of weakly

relativistic oversized BWO based on the sinusoidal SWS in Ref.(9), the nonaxisymmetric mode became dominant mode. The mode control of the oversized BWO is a serious issue to be solved. In this work, the nonaxisymmetric and axisymmetric operations of the oversized BWO are observed. It is demonstrated that these modes can be controlled by changing the input cylinder length.

In conclusion, we study an oversized BWO with a novel disk cathode and a rectangular corrugation. The beam voltage is weakly relativistic, less than 100 kV. The beam current is up to about 500 A. In order to get a uniformly distributed annular electron beam, we propose a disk cathode made of metal. The novel cathode is able to be used even in the weakly relativistic case. By using the annular electron beam, a weakly relativistic oversized BWO consisting of rectangularly corrugated cylindrical waveguide is demonstrated. The oscillation starting energy is about 60 kV for a 10-period rectangular corrugation. The output power increases with increasing the beam voltage, if the beam interaction point approaches to the π point. The estimated output power reaches at about 200 kW. The mode control between axisymmetric and nonaxisymmetric modes is performed by changing the end condition of BWO. The weakly relativistic oversized BWO mentioned above is unique and of considerable interest for practical use.

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