Experimental investigation of backward wave oscillator with low magnetic field

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Abstract A backward wave oscillator (BWO) is introduced in the paper. On the accelerator of Sinus-700, it is experimentally investigated. Under the condition that the electron energy is 740 keV, the beam current is 7 kA and the guiding magnetic field is at 0.68 T, the performance of 1.15 GW microwave output power at 9.1 GHz microwave frequency with 22 ns pulse width and 22% conversion efficiency are reached.

Key words high power microwave, BWO, low magnetic field, accelerator

PACS 41.60.Bq

1 Introduction

In recent years, sources generating high power microwave (HPM) have been developed extensively. There are two kinds of microwave devices used in these sources. One has big impedance and big conversion efficiency, but it requires a strong guiding magnetic field[1—4]. The other one with a small impedance requires higher pulsed electric power and its conversion efficiency is small[5, 6]. Therefore, one of the key issues, which needs to be investigated is how to design a low magnetic field operated HPM device which has big conversion efficiency. A. I. Gunin achieved 0.5 GW microwave output power at 10 GHz microwave frequency with 10 ns pulse width at 0.7 T permanent magnetic field in 1998; In 2001, FAN Ju-Ping from Northwest Institute of Nuclear Technology (NINT) reported 170 MW microwave output power with 8.874 GHz microwave frequency at 0.7 T guiding magnetic field[7]; In 2006, ZHANG Jun from National University of Defense Technology obtained 1.2 GW X-band microwave output power at 0.6 T guiding magnetic field[8]. All the above-mentioned devices increased the radial dimensions of the devices so as to decrease the guiding magnetic fields. However, it inevitably enhanced the difficulty to use a permanent magnetic field as the guiding magnetic field.

A HPM device with small radial dimension, whose output microwave power and conversion efficiency are not remarkably decreased when it is operated at low guiding magnetic field, is put forward in this paper. It is hopeful for it to be developed to a practical HPM source guided by a permanent magnetic field.

2 Description of experimental system

The electron beam used in the experiment of the backward wave oscillator (BWO) with low magnetic field is generated by the high-current electron accelerator Sinus-700 which consists of a pulse generator, a switch and a high-current electron diode. The accelerator can afford an electron beam whose energy and current are 1 MeV and 10 kA, respectively.

The electron diode and the BWO are immerged in a guiding pulsed magnetic field which is generated by a solenoid. The pulsed magnetic field whose width is about 20 ms can be continuously adjusted between 0 and 3.2 T.

The BWO generates microwave with mode of TM_{01}, which radiates in air through an antenna.

3 Design of the BWO with low guiding magnetic field

After theoretical analysis and numerical simulation, the BWO with low magnetic field (Fig. 1(a)) is designed. The fundamental parameters of the BWO are as follows: 1) The average radius of the slow

Received 23 April 2007
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wave structure (SWS) r_a=1.65 cm; 2) The depth of SWS d=0.3 cm; 3) The corrugation period of SWS L=1.6 cm. The SWS of the BWO is divided into two sections by a drift tube. When a relativistic electron beam (REB) travels through the first section of SWS, its velocity is modulated. Its velocity modulation is converted into density bunching gradually when REB travels through the drift tube. At last, the energy of the well-bunched REB is extracted in the second section of SWS. There is a Bragg reflector on the beginning of the SWS which is used to completely reflect the backward wave. There is also a reflector on the end of the SWS, which is used to partially reflect the forward wave so as to increase the Q-value of the device and decrease the strength of the guiding magnetic field.

The electron energy in the simulation is 760 keV and the current of the REB whose average radius and thickness are respectively 1.125 cm and 1.5 mm is 7.2 kA. The typical results which are achieved at the magnetic field B=0.73 T are showed in Fig. 1(b) and Fig. 1(c) which indicate the output microwave power and frequency are respectively 1.2 GW and 9.3 GHz. From Fig. 1(b) and Fig. 1(c), we also know that the mode and the conversion efficiency are respectively TM_{01} and 25%.

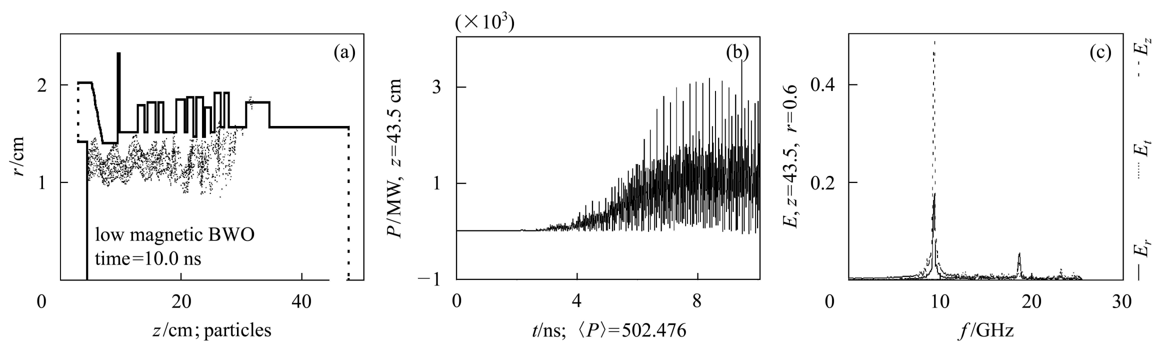

Fig. 1. (a) The model of BWO; (b) The output power vs time; (c) The frequency spectrum.

4 Description of measure system

In experiment, there are two kinds of parameters which need to be measured. One, which is about electron beam, includes beam current and electron energy. The other one, which is about output microwave, includes microwave power and its frequency.

Beam current measurement Because the Faraday cup which is used to measure the beam current interdicts the electron beam, a method deducing the beam current from the total current, which is measured by a Rogowski coil placed at the beginning of the diode and includes the beam current and the losing current, is put forward. Firstly, the total current and the beam current at different values of the guiding magnetic field are measured on the condition of the optimal electron energy for the BWO. Secondly, the relationship between the beam current and the total current is set up.

Ratios of the Rogowski coil and the Faraday cup are 10 kA/V and 17.7 kA/V, respectively.

Electron energy measurement The electron energy is measured by a voltage-divider whose ratio is 1 MV/V.

Microwave frequency measurement The heterodyne technique is used to obtain the microwave frequency. Attenuated by cable and attenuators, the radiated microwave received by a receiving antenna is mixed with a fundamental, which results in an intermediate-frequency (IF) signal outputted from

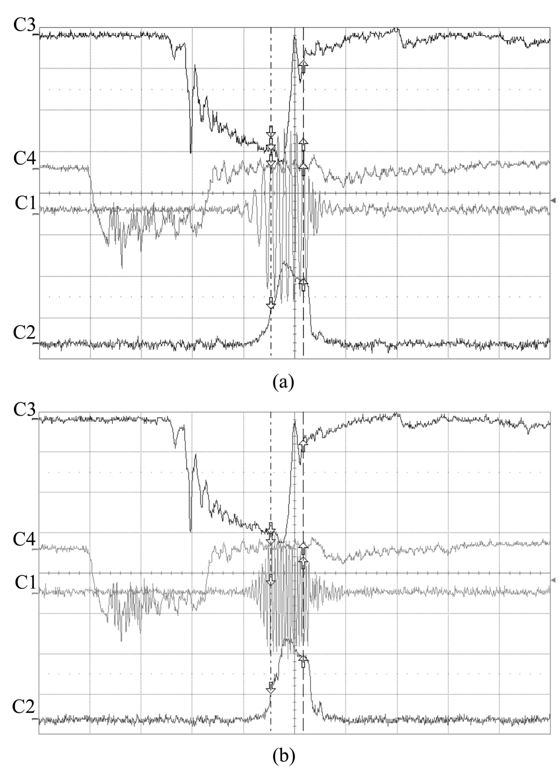

Fig. 2. The typical heterodyne signal (C3-IF signal, (a) when the fundamental is 9.5 GHz; (b) when the fundamental is 10 GHz).

mixer. Then the radiated microwave frequency can be deduced from the IF signal.

Figure 2 shows the typical IF signals of the same radiated microwave when fundamentals are different. From Fig. 2, we can acquire the output microwave frequency as 9.1 GHz.

The measured frequency ranges from 9.1 GHz to 9.2 GHz when the guiding magnetic field changes from 0.4 T to 0.72 T.

Output microwave power measurement

When the microwave frequency ranges from 9.1 GHz to 9.2 GHz, the total attenuation factor is 73 dB and the effective area of the receiving antenna is 2.7 cm^2 . The detecting curve of the detector is shown in Fig. 3.

The distance between the radiating antenna and the receiving antenna is 3 m.

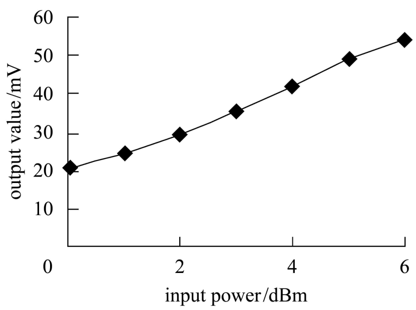

Fig. 3. The detecting curve of the detector.

5 Experimental investigation of the BWO

5.1 Adjustment of the electron diode

Because the output microwave power is extracted from electron beam, the electron diode has to be adjusted.

The coaxiality of electron beam and the BWO is solved by letting the electron beam bombard the target placed at the end of the BWO. Fig. 4 shows the waveforms of the electron beam and the mark of the electron beam on the target when the magnetic field is 1.5 T. From Fig. 4 we know the deviation of the axes of electron beam from that of the BWO is about 0.5 mm.

To acquire the value of the beam current, the relationship between the total current and the beam current on the condition of the appropriate electron energy must be set up. Fig. 5 shows the typical waveforms and the relationship. From Fig. 5, we can see the beam current is only a fraction of the total current and increases according to the guiding magnetic field. It's noteworthy that, the relationship is useful only when the electron energy and the total current are respectively between 650—750 keV and between 9.9—14 kA.

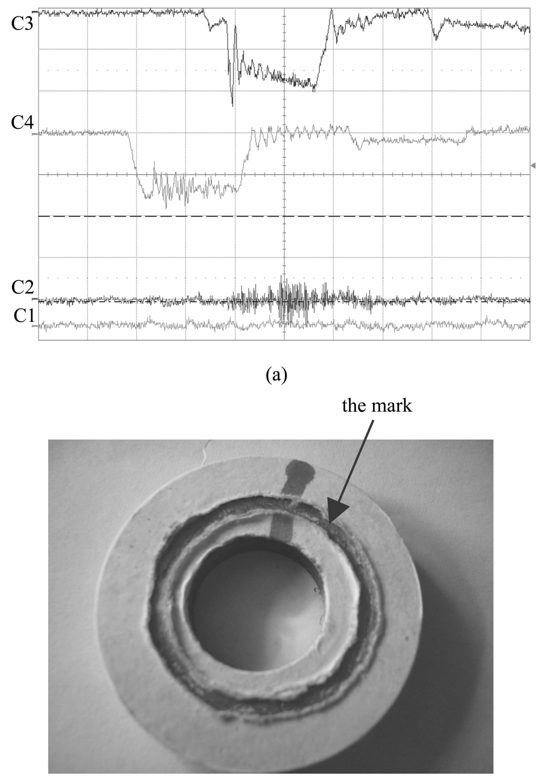

Fig. 4. (a) The waveform of the electron energy C4 and that of the beam current C3 (b) the mark of the electron beam.

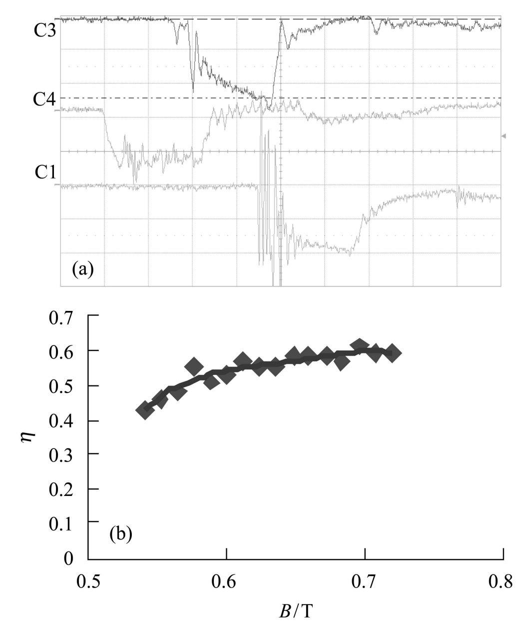

Fig. 5. (a) The typical waveform of the total current C3 and that of the beam current C1 (C4 is the waveform of the electron energy); (b) relationship between η (the ration of the beam current and the total current) and magnetic field B.

5.2 Determination of the power density pattern

The microwave power density pattern (Fig. 6) on the left side is measured for horizontal polarization in the plane at a distance of 3 m from the radiating antenna in the horizontal direction. Fig. 6 shows the mode of the microwave is TM_{01}.

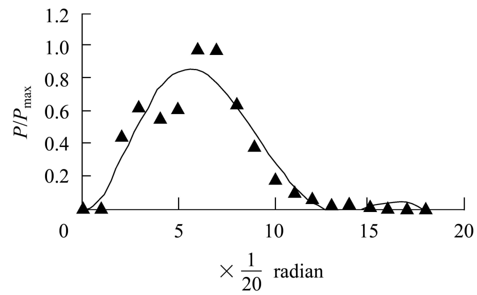

Fig. 6. Normalized power density pattern of radiation.

The microwave power is computed by means of integration over the radiation pattern obtained in experiment. When the receiving antenna is placed at the place where the power density is the biggest in Fig. 6, the relationship between the output value of oscilloscope and the output microwave power is shown in Fig. 7.

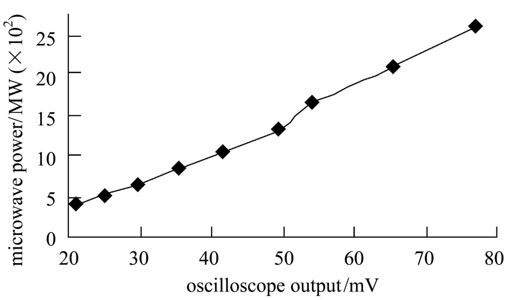

Fig. 7. The relationship between the oscilloscope output and the microwave power.

5.3 Relationship between the output microwave power and the guiding magnetic field

In BWO, there must be a magnetic field to guide the electron beam, so the relationship between the magnetic field and the output microwave power must be investigated.

The numerical simulation shows the output microwave power is nearly zero for the guiding magnetic field between 0.8 T and 2.2 T when the electron energy and beam current are respectively 760 keV and 7.2 kA, which is consistent with the experimental result (Fig. 8). Fig. 8 shows the experimental output microwave power is zero when the guiding magnetic field ranges from 0.74 T to 2.36 T.

Here we're only interested in the case that the guiding magnetic field is less than 0.74 T (Fig. 9). When the electron energy and the beam current of diode are 740 keV and 7 kA, respectively, and the guiding magnetic field is 0.68 T, the performance of 1.15 GW microwave output power at 9.1 GHz microwave frequency with 22 ns pulse width (Fig. 10) and 22% conversion efficiency are reached.

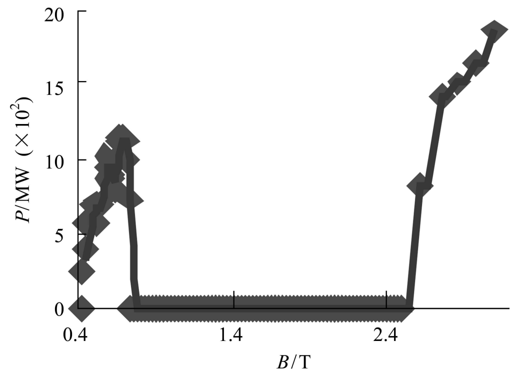

Fig. 8. The relationship between the output power and the guiding magnetic field.

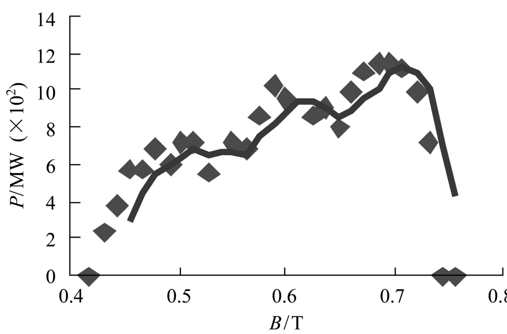

Fig. 9. The relationship between the output power and the guiding magnetic field when the magnetic field is small.

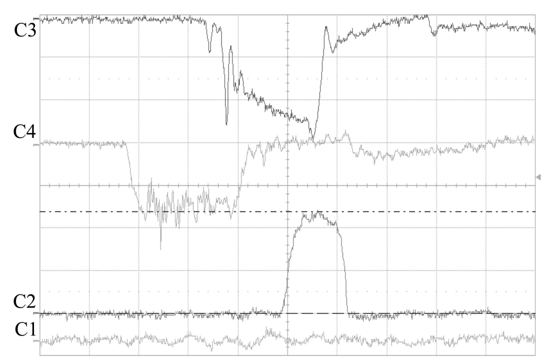

Fig. 10. The waveform (C4-of electron energy C3-of total current C2-of microwave detector signal).

5.4 Relationship between the microwave frequency and the guiding magnetic field

The value of the guiding magnetic field influences the quality of the electron beam, so as to influence the microwave frequency. Fig. 11 shows the relationship between the microwave frequency and the guiding magnetic field. It can be seen from Fig. 11 that, when the guiding magnetic field gradually increases, the frequency increases until it becomes stable at an invariable vale.

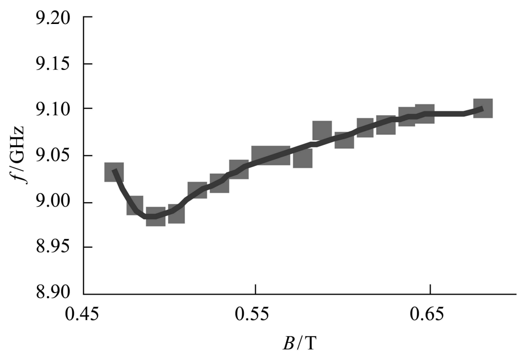

Fig. 11. The relation between the microwave frequency and the guiding magnetic field.

The relationship between the microwave frequency and the magnetic field can be interpreted from the relationship between the electron velocity and the magnetic field. Because the axial fraction of the electron velocity increases with the magnetic field, the frequency which is determined by the intersection of the dispersion of the BWO and $\omega = k_z v_0$ of the electron beam also increases. However, when the axial velocity of the electron approximates its velocity, the frequency is stable.

6 Conclusion

The BWO is experimentally investigated on the accelerator of Sinus-700. When the electron energy and the beam current of diode are 740 keV and 7 kA, respectively, and the guiding magnetic field is 0.68 T, the performance of 1.15 GW microwave output power at 9.1 GHz microwave frequency with 22 ns pulse width and 22% conversion efficiency are reached.

The BWO is on the same level with other microwave devices with low magnetic field in the world; but it has the smallest radial dimension. So it is possible to develop practical HPM source guided by a permanent magnetic field.

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