About the selection of transverse modes in the X-band oversized oscillator with 2.5 GW output power

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Abstract. The paper describes the numerical and experimental results of the microwave O-type oscillator based on an oversized slow wave structure (SWS). The feedback is applied to the design scheme, which provides intense modulation of the electron beam in the cathode-anode region and two special cavities before SWS. The selectivity of TM02 operating mode occurs due to increased diffraction loss of parasitic modes in the cathode part. The slow wave structure consists of two identical sections with the phase-shifting region in between. The use of this configuration leads to the formation of a locked TM01 wave, having good conditions for the transformation into the working mode TM02. In the experiments, a stable generation regime with pure TM02 mode at a frequency of 10 GHz with an efficiency of about 30% and the output power of 2.5 GW in the magnetic field below the cyclotron resonance was obtained.

1. Introduction

The use of the high-current electron beams demonstrates that the most advanced systems, considering the power augmentation and the energy conversion efficiency of the electron beam into the energy of the electromagnetic-microwave pulse are the relativistic Cherenkov-type oscillators, and in particular, the backward wave oscillator (BWO). The generation in such systems is usually performed at lowest modes due to the lower starting current against the higher modes. In X-band, raising of the generated power up to the level of ≈ 1 GW results in the necessity for enlarging the diameter D of the slow wave structure (SWS) in comparison with the wavelength λ to prevent the microwave breakdown [1].

The reduction of maximal electric fields at the SWS has been achieved in the BWO with resonant reflector at

\[ D \approx 1.5 \lambda \]

which allowed us to increase the output microwave power up to 3 GW at the pulse width of 20 ns [1, 3]. The further grow of \( D \) leads to the mode competition. The special methods of mode selection should be used to discriminate parasitic modes.

In this paper, the new approach for development of the low Q-factor oversized resonant SWS (\( D \approx 2.5 \lambda \)) is considered.

The slow-wave system under study (figure 1) consists of two similar sections arranged in the way to meet the conditions for the radiation of the slow wave TM01 only into the TM02 wave. The low-Q cavity includes a hollow cylindrical cathode, which functions as a reflector as well. The output signal is partially transmitted to the cathode and modulates the electron beam in the SWS.

The fundamental research and simulation of steady-state processes of such systems (BWO with modulation of emission, [4]) reveals the potential to increase the performance up to 50%.
Figure 1. Experimental setup: 1- cathode; 2- electron beam; 3- SWS; 4- solenoid; 5- collector; 6- horn antenna; 7- receiving antenna; 8- detector on hot media; 9- heterodyne; I- reflection region backward wave; II- region of oversized SWS.

At the cathode side of the SWS, a matching element in the form of several grooves is placed. Here, the wave TM$_{02}$ counter to the electron beam is transformed into the mode mixture causing the minimal diffraction losses into the region of the hollow cathode. The cathode-anode gap can be considered as a region of the combined quasi-optical system where the parasitic modes provide essential diffraction losses. The losses of the operating wave are of 1 – 2%. To improve the selective properties of the hollow cathode, a resonant reflector was used instead of the plane [5]. The operating wave is reflected from the reflector inserted into the cathode, so, the efficient wave selection is provided.

2. Computational modelling

The final sizing and the optimization of the mode for the stationary generation were performed with the KARAT 2.5D code [6]. The average radius of the oversized slow wave system was 3.7 cm. The corrugation amplitude was about 0.6 cm. The diode was fed by TEM wave to obtain the cathode voltage of 680 kV. The electron beam was emitted from the cathode side-face with the outer radius of 3.2 cm. The electron beam current was about 12 kA. At the output crosscut behind the collector, a pure enough mode of the circular waveguide TM$_{02}$ was registered. The guiding magnetic field of the solenoid selected above the cyclotron resonance was about 3 T [7]. As figure 2(a) shows, the transient process lasts several nanoseconds (the voltage rise time is 4 ns). The optimal generation mode at the frequency of 10 GHz corresponded to the power of 3.8 GW (figure 2(a, b)) in the numerical experiment.

Figure 2. (a)- changing the output power of the microwave oscillations in time; (b)- the emission spectrum

Here, the maximal voltage of the electrical field at the SWS rounding is estimated to be about 0.7 MV/cm. Such a field level provides the operation without microwave breakdown with the pulse durations up to $10^8$ ns and requires a certain surface treatment when increasing the radiation duration. The maximal calculated performance efficiency was 47%. The calculation results reveal the dependence of the generator efficiency on the diode accelerating voltage as well as on the position of
the reflector inside the cathode hollow. When other parameters are fixed, the geometric variations of
corrugation near the adapter significantly affect the generator efficiency. The optimal geometry
deviation of 5% results in the efficiency fall up to 30%.

3. Experimental research at SINUS-7

Before the experiment, the special treatment of the SWS surface was provided. The internal part of the
electrodynamic structure (figure 3) was treated with the low-energy electron beam of 35 keV [8] using
the OCTAGON-2. This technique provided the higher quality of the surface finish and the reduction of
the regions where locally the electric field strengthening occurred. The surface finish as well as the
structural composition was monitored with the electron-beam microscope.

In preliminary studies, with untreated SWS surface, we observed an unstable operation of the
generator [9].

It was previously demonstrated [10] that the limitation of the microwave pulse duration in a
nanosecond pulsed RBWO operating at a gigawatt power level could be related to the development of
an explosive emission from the SWS surface under the action of intense microwave fields. A key role
in suppression of the microwave generation is played by positive ions emitted from the near-surface
plasma, which remove the space-charge limitation on the electron emission current. Thus, the
microwave pulse duration is limited by the total time of the development of explosive emission and
the accumulation of ions in the SWS volume [11, 12].

Figure 3. Common view of electrodynamic structure

After preparation, the electrodynamic system was studied at the SINUS-7 accelerator. The
operating diode voltage and the electron beam current of 670 kV and 13 kA, respectively, were close
to the simulations. The microwave radiation pulses were recorded by the magnetic loop antenna
placed in the far field zone. The microwave pulse energy was measured by the aperture liquid
calorimeter with the enhanced recording system. The calorimeter was placed near the output horn
antenna. The stable microwave signals at the defined frequency of 10 GHz (figure 4(a)), which were
repeated from pulse to pulse, were generated under the magnetic field of about 1 T. To measure a
frequency, a heterodyne measuring technique was used. In the experiment, the heterodyne reference
frequency was 9 GHz, so the frequency values indicated in the waveform were about 1 GHz that
corresponded to 10.0 GHz of the output microwave pulse.

In the magnetic fields below the cyclotron resonance, the microwave radiation power measured by
the calorimeter agrees well with the calculated power and is 2.7 GW. The directivity diagram obtained
in the far field zone of the horn antenna indicates the generation of the symmetric mode TM02. The
numerical calculations with KARAT demonstrate that the optimal magnetic field for this generator is
3 T. Here, the calculated power should be about a third higher than in the fields below the cyclotron
absorption. However, providing this mode experimentally, the amplitude of the microwave signal
decreased, and another lower frequency of 8.5 GHz appeared which corresponded to the non-
symmetrical wave TE11 (figure 4(b)).

A resonant reflector was installed into the cathode instead of the former reflector in the shape of a
plane wall. The calculation results obtained with the ANSYS HFSS [13] software reveal that this
resonant reflector at 10 GHz provides almost full reflection of the operating mode TM02-TM01 while the
non-symmetrical parasitic modes pass into the cathode at most.
In the experiment, a microwave absorber was placed behind the reflector. So, the mode selection was provided due to the diffraction losses of the parasitic oscillations in the coaxial region as well as inside the cathode.

The dependence of the microwave radiation normalized power on the diode voltage at different positions of the reflector inside the cathode (figure 5) confirms a good agreement between the experimental data and the numerical simulations.

The curves in figure 5 indicate that within a certain voltage range, there is an optimal reflector position $dL_w$, which corresponds to the reflection phase of the counter wave, resulting in the maximal output microwave power.

In the numerical simulations, the output microwave power reached 3.8 GW in a strong magnetic field above the cyclotron resonance. In experiments, however, the output microwave power was unstable (figures 4 (b), 6) when the guiding magnetic field was 3 T.
The research demonstrated that the electron beam modulation in the cathode-anode region decreases the starting current for the operating mode and provides the increase of the generator efficiency. The unstable mode in the strong magnetic fields was revealed even under the slight beam axis misalignment.

**Figure 6.** Output power $P$ on the magnetic field $B$. Solid curve – numerical calculation on PIC-code KARAT at 670 kV, 12 kA, vertical lines – range of experimental results.

This can indicate the modest suppression of the competitive non-symmetrical modes.

**4. Conclusion**

So, the microwave radiation power in the stable generation mode reached about 2.5 GW in the experiment as well as in the simulations. It showed the 30% efficiency at the frequency of 10.0 GHz just in the magnetic fields of about 1 T. The numerical simulations demonstrate the perspective of the efficiency up to 48% when generator operating in a strong magnetic field of 3 T. It can be provided by improving the selectivity of the generator.

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