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PLASMA ELECTRONICS

Tunable Plasma Relativistic Microwave Amplifier

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Abstract—A stable regime of the amplification of a slow plasma wave in a plasma waveguide during the injection of a high-current relativistic electron beam is obtained. For an input-signal frequency of 9.1 GHz, there exists a range of plasma densities in which the spectrum of the output microwave radiation lies in a 0.5-GHz-wide band. For a 40-kW input power at a frequency of 9.1 GHz, the maximum output power is 8 MW. It is shown experimentally for the first time that the beam–plasma amplifier can operate at frequencies of 9.1 GHz and 12.9 GHz. The range of plasma densities in which the regime of amplification is observed agrees with the results of calculations based on linear theory. © *2000 MAIK "Nauka/Interperiodica"*.

1. INTRODUCTION

A cylindrical coaxial plasma waveguide, whose central electrode is a column of magnetized plasma with a sharp boundary, is a slow-wave electrodynamic structure. In such a waveguide, there exist slow (with a phase velocity lower than the speed of light) eigenmodes whose electric field has a nonzero longitudinal component (*E*-modes). The maximum phase velocity of these modes increases with increasing the plasma density n_p and approaches the speed of light as $n_p \longrightarrow \infty$. Hence, when an electron beam is injected into the plasma waveguide, the Cherenkov synchronism between the beam and a waveguide eigenmode can occur if the plasma density exceeds a certain threshold value. Theoretical research on the mechanism for the excitation of the eigenmodes of a coaxial plasma waveguide by a relativistic electron beam (REB) has been carried out since the 1970s (see review [1]).

Note that, initially, the interaction of a nonrelativistic electron beam with a plasma was studied both theoretically and experimentally. These studies can be divided into two groups. In the first group, the plasma was used to change the configuration of the electric field in vacuum microwave sources in order to improve their parameters. This made it possible to increase the efficiency of such sources and to create high-power microwave amplifiers and noise masers with a frequency tuning of ±30% and a rather high efficiency (~40%) [2, 3]. On the other hand, such use of the plasma could not significantly broaden the frequency tuning range. In the second group of investigations, the microwave power was generated through the coupling between a nonrelativistic electron beam and slow modes of a plasma waveguide. This showed promise for creating microwave devices capable of tuning the operating frequency over a wide range. However, such devices have not been created because it is impossible to provide an efficient output of such a broadband microwave radiation from the plasma.

It is important to note that the radial structure of the field of slow waves in a coaxial plasma waveguide is similar to the structure of the TEM mode of a coaxial metal waveguide with a similar geometry if their phase velocities are close to the speed of light ($v_{ph}/c \geq 0.8$). This circumstance significantly simplified the problem of the output of microwave power from the plasma waveguide and showed promise for the use of REBs for the generation and amplification of electromagnetic waves in beam–plasma systems.

The first successful experiment on microwave generation with the use of an REB exciting eigenmodes of a plasma waveguide was carried out in 1982 [4]. The experiment confirmed the main theoretical predictions about the mechanism for the beam–plasma coupling and showed that it is possible to attain a high (about 10%) efficiency of generation. The experiment also demonstrated the main features of a Cherenkov plasma maser (CPM): a broad frequency band (~40%) and the possibility of tuning the generated frequency over a wide range. As the plasma density varied from its threshold value $n_p \approx 1 \times 10^{13}$ cm^{-3} to $n_p \approx 8 \times 10^{13}$ cm^{-3}, the generated frequency varied from 10 to 20 GHz.

In subsequent experiments on the generation of microwave radiation in a relativistic beam–plasma system, the accuracy of the measurements of the absolute power and emission spectrum was increased and the parameters of the beam, plasma, and output facility were optimized [5–7]. The theory, in turn, developed nonlinear time-dependent models best suiting the experimental conditions [8, 9]. At present, a good agreement has been achieved between the theory and the experiment. It is shown that a CPM generates a broad emission spectrum with a relative width no less than 20% and that the central generated frequency can be varied sevenfold by varying the plasma density in the plasma waveguide. Attempts to make the emission spectrum width comparable with that of vacuum relativistic oscillators (~3%) have been unsuccessful.

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In order to narrow the CPM emission spectrum, it was proposed that the signal from an external source be fed to the CPM. In this case, the beam–plasma system can operate either in the amplification or generation mode, but the central radiation frequency in both modes is governed by the frequency of the input signal.

The first successful experiment on the amplification of microwave signals in a beam–plasma system [10] demonstrated the possibility of amplifying an external signal at plasma densities within a relatively narrow interval near the threshold density. However, the amplification regime was insufficiently stable and was accompanied by spontaneous generation at frequencies other than the frequency of the input signal.

An efficient method for suppressing spontaneous generation is the use of a large-volume microwave absorber. For this reason, it is of interest to study experimentally the amplification of plasma waves by an REB in a system partially filled with a microwave absorber. This is the aim of the present paper.

2. EXPERIMENTAL LAYOUT

A schematic of the device is shown in Fig. 1. An annular plasma column (*1*) with a mean radius of 7.5 mm and thickness of 1 mm is immersed in a uniform longitudinal magnetic field $B = 1.6$ T in a cylindrical metal waveguide (*2*) of radius 22 mm. The plasma is produced in a hot-cathode discharge in xenon. The cathode potential is 600 V, the discharge current is up to 100 A, and the xenon pressure is 3.5×10^{-4} torr. The parameters of an REB (*3*) propagating along the waveguide axis are the following: the electron energy is 550 keV, the current is 1.5 kA, the pulse duration is 150 ns, the mean beam radius is 10 mm, and the beam-wall thickness is 1 mm. A microwave converter (*4*) is mounted at the entrance to the plasma waveguide. The converter excites a TEM mode, which is transformed into the fast and slow modes of the plasma waveguide. The slow plasma mode is amplified by the REB, is converted into a TEM mode of the output metal coaxial waveguide, and is emitted by a large-cross-section output coaxial horn (*5*). The length of the beam–plasma interaction is equal to 29 cm. The system design allows the installation of an annular microwave absorber (*6*) with an outer radius of 22 mm, inner radius of 11.5 mm, and length of 14 cm. The absorber is placed at a distance of 3 cm from the conical collector of the REB at the exit from the system. The microwave-power absorption coefficient was 20 dB for the TEM mode in a coaxial waveguide with an inner radius of 5 mm and outer radius of 22 mm and was equal to 50 dB for the TM_{01} mode in a hollow waveguide of radius 22 mm. Measurements were carried out at a frequency of 9.1 GHz.

As a source of input microwave signals, we used one of two pulsed magnetrons. The first magnetron had a frequency of $f_0 = 12.9$ GHz, pulse duration of 2 μs, and power of $P_{in} = 75$ kW. The corresponding parameters of the second magnetron were 9.1 GHz, 20 μs, and 40 kW, respectively.

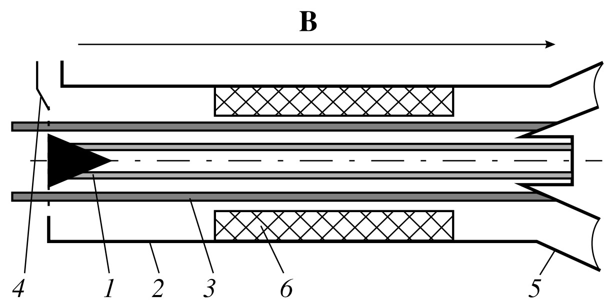

Fig. 1. Schematic of the plasma relativistic microwave amplifier: (*1*) plasma, (*2*) metal waveguide, (*3*) REB, (*4*) entrance of the amplifier, (*5*) coaxial conical emitting horn, and (*6*) microwave absorber.

The output microwave power and radiation spectrum were recorded by two detectors placed in a 23×10 mm^2 receiver waveguide. The first detector (a broadband receiver) measured the total microwave power entering the receiver waveguide. At the input of the second detector (a narrowband receiver), one of two narrowband microwave filters (with a passband $\Delta f = 0.29$ GHz for $f_0 = 12.9$ GHz or $\Delta f = 0.51$ GHz for $f_0 = 9.1$ GHz) tuned to the magnetron frequency was installed. Both receivers had nearly the same power sensitivity. For this reason, when the radiation spectrum at the receiver entrance was narrower than the passband of the microwave filter, the narrowband-to-broadband signal ratio was equal to unity. When the radiation spectrum at the receiver entrance was broader than the passband of the microwave filter, this ratio was lower. Hence, it was possible to estimate the width of the spectrum of output microwave radiation.

To carry out absolute measurements of the output microwave power, we used a broadband wide-aperture microwave calorimeter [11]. The calorimeter measured the total energy of the output microwave pulse, and the envelope of the microwave pulse was recorded by the detector. This allowed us to determine the output microwave power.

3. EXPERIMENTAL RESULTS

Figure 2a shows the output energy of spontaneous microwave radiation on the plasma density (crosses) in the absence of an absorber. It is seen from the figure that self-excitation occurs if $n_p \geq 4 \times 10^{12}$ cm^{-3}. When an external 40-kW microwave signal at a frequency of $f_0 = 9.1$ GHz is fed to the input of the beam–plasma system, the density range in which the generation is observed expands toward lower plasma densities. The corresponding experimental data are shown by circles in Fig. 2a. Hence, there exists a range of plasma densities, $2.5 \times 10^{12} < n_p < 4 \times 10^{12}$ cm^{-3}, in which the output

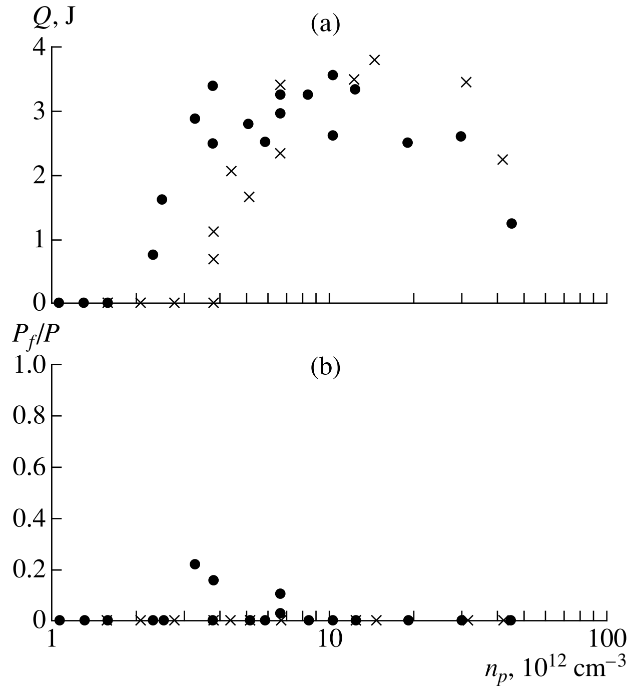

Fig. 2. (a) The output microwave radiation energy measured by the calorimeter as a function of the plasma density and (b) the ratio between the power measured by the narrowband and broadband receivers vs. the plasma density at t = 75 ns after applying the voltage pulse to the diode in the case when a 40-kW signal at a frequency of 9.1 GHz is fed to the entrance of the system (circles) and without an input signal (crosses); the microwave absorber is absent.

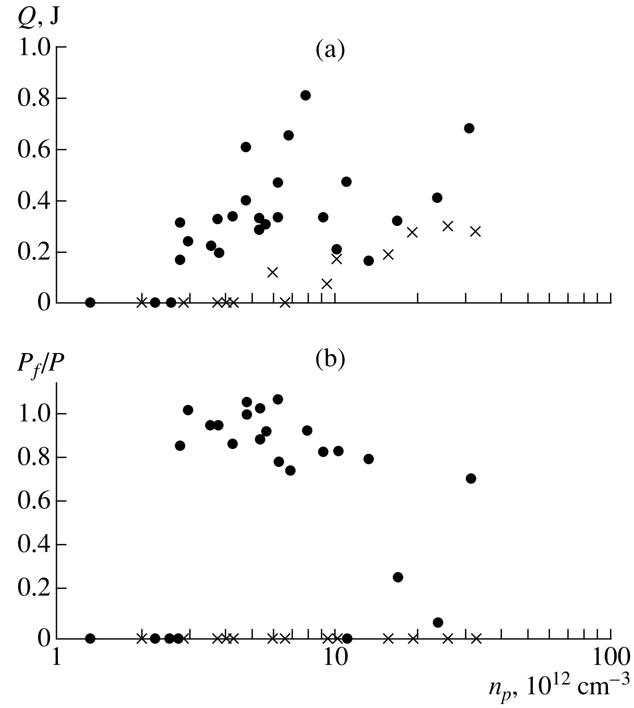

Fig. 3. (a) The output microwave radiation energy measured by the calorimeter as a function of the plasma density and (b) the ratio between the power measured by the narrowband and broadband receivers vs. the plasma density at t = 75 ns after applying the voltage pulse to the diode in the case when a 40-kW signal at a frequency of 9.1 GHz is fed to the entrance of the system (circles) and without an input signal (crosses); the microwave absorber is present.

signal is detected only if the input signal is fed; this may be interpreted as signal amplification. The output power in this operation mode attains 60 MW.

As was mentioned above, in order to estimate the width of the emission spectrum, the output radiation was measured by two (broadband and narrowband) microwave receivers that had the same sensitivity. Figure 2b shows the ratio between the powers detected by the narrowband and broadband receivers as a function of the plasma density. This ratio was calculated at the time t = 75 ns after applying the voltage pulse to the diode. The circles correspond to the presence of a signal at the entrance to the beam–plasma system. It is seen from the figure that the power ratio is no higher than 0.3; this means that only about 35% of the radiation power falls into the sensitivity band of the narrowband receiver.

The data presented in Fig. 2 allow us to conclude that, at $n_p > 4 \times 10^{12}$ cm^{-3}, the beam–plasma system under study operates in the regime of spontaneous generation. At $2.5 \times 10^{12} < n_p < 4 \times 10^{12}$ cm^{-3}, it operates in a mixed mode. In the regime of spontaneous generation, the output signal is unaffected by the input signal and, in most of the pulses, the ratio between the signals from the narrowband and broadband receivers is no higher than 0.05. In the mixed mode, a substantial (about 35%) fraction of the emission power lies within a 0.5-GHz-wide band and the output signal is detected only in the presence of the input signal.

To suppress spontaneous generation, we used a large-volume microwave absorber (Fig. 1, position *6*). Figure 3a shows the output radiation energy as a function of the plasma density in the absence (crosses) and presence (circles) of a 40-kW input signal at a frequency of f_0 = 9.1 GHz. It is seen from Fig. 3a that, with an absorber, the energy of spontaneous emission generated in the range of plasma densities $2 \times 10^{12} < n_p < 1.7 \times 10^{13}$ cm^{-3} is lower by a factor more than 15 than without an absorber. At the same time, the energy of the amplified signal decreases only by a factor of 5, which is evidence of the positive effect of the absorber. Figure 3a demonstrates that, in the range of plasma densities $3 \times 10^{12} < n_p < 3 \times 10^{13}$ cm^{-3}, the amplified radiation dominates over the spontaneous emission. In this case, the maximum power of the amplified signal is 8 MW, whereas the maximum power of spontaneous emission is 1 MW.

Figure 3b shows the ratio between the signals from the narrowband and broadband receivers in the presence of an absorber at t = 75 ns after applying the voltage pulse to the diode. It is seen that, in the range of plasma densities $3 \times 10^{12} < n_p < 1.2 \times 10^{13}$ cm^{-3}, the output signal from the beam–plasma system always lies within the sensitivity band of the narrowband receiver (the power ratio is close to unity). This property fundamentally distinguishes this system from the above system without an absorber as well as from the system described in [10]. Note that the value of P_f/P was measured accurate to within 15%. That is why, for some shots in Fig. 3b, we have $P_f/P > 1$.

Figure 4a shows the waveforms of the signals from the broadband (*1*) and narrowband (*2*) receivers and the voltage pulse at the diode (*3*) for a plasma density of 5×10^{12} cm^{-3}. As was noted above, the receivers have the same sensitivity; consequently, the fact that the first waveform is identical to the second one shows that the spectrum of the output radiation lies within the passband of the narrowband microwave filter throughout the entire voltage pulse. We note that, for $9 \times 10^{12} < n_p < 1.5 \times 10^{13}$ cm^{-3}, spontaneous generation occurs by the end of the voltage pulse and the spectrum of the output radiation broadens. This is illustrated by Fig. 4b, which corresponds to a plasma density of 10^{13} cm^{-3}. It is seen that, during a time of ~80 ns from the beginning of the voltage pulse, the signals from the narrowband and broadband receivers are identical; later, they show a different behavior. This indicates that the radiation spectrum is wider than the passband of the microwave filter.

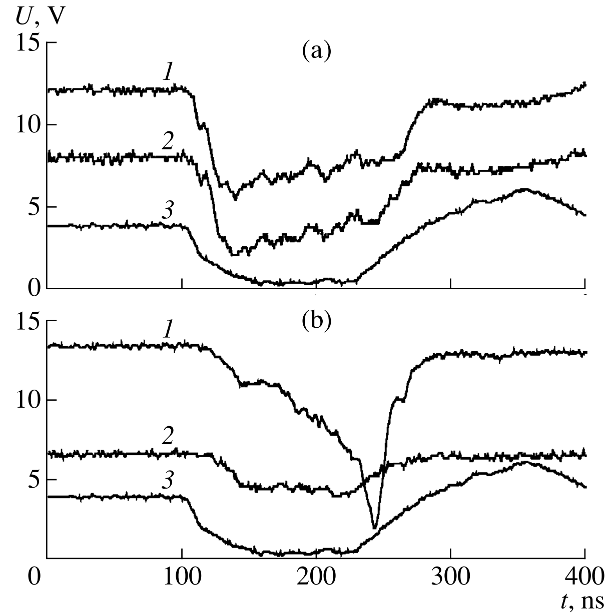

Fig. 4. Waveforms of the signals from (*1*) the broadband and (*2*) narrowband receivers and (*3*) the voltage pulse at the diode for f_0 = 9.1 GHz, P_{in} = 40 kW, and n_p = (a) 5×10^{12} and (b) 10^{13} cm^{-3}; the microwave absorber is present.

Figure 5 shows the theoretical frequency dependence of the linear single-pass wave-power amplification coefficient for different plasma densities. (The plots in Figs. 5 and 6c were calculated with the help of a numerical code developed by M. A. Krasil'nikov.) It follows from Fig. 5 that it is possible, first, to realize the amplification regime (within a frequency band of about 40%) for a given plasma density and, second, to tune the amplified frequency from 8 ± 1.5 to 35 ± 4 GHz by varying the plasma density from 8×10^{12} to 7×10^{13} cm^{-3}. To verify these theoretical predictions, we carried out experiments on the amplification of a signal at a frequency of 12.9 GHz. A 75-kW signal was fed to the input of the beam–plasma system with a microwave absorber. Figure 6a shows the output radiation energy as a function of the plasma density in the absence (crosses) and presence (circles) of the input signal. It is seen from Fig. 6a that, in the range of plasma densities $10^{13} < n_p < 1.6 \times 10^{13}$ cm^{-3}, spontaneous generation is absent but there is an amplified signal with a power of up to 4 MW. Figure 6b (similar to Figs. 2b and 3b) illustrates the ratio between the signals from the narrowband and broadband receivers at t = 75 ns after applying the voltage pulse to the diode. A comparison of Figs. 3b and 6b shows that the operation of the system at a frequency of f_0 = 12.9 GHz is less stable and the P_f/P ratio lies within the range 0.2–0.9 for the plasma density in the range $10^{13} < n_p < 3 \times 10^{13}$ cm^{-3}. Nevertheless, we can conclude that the amplification also takes place at a frequency of 12.9 GHz.

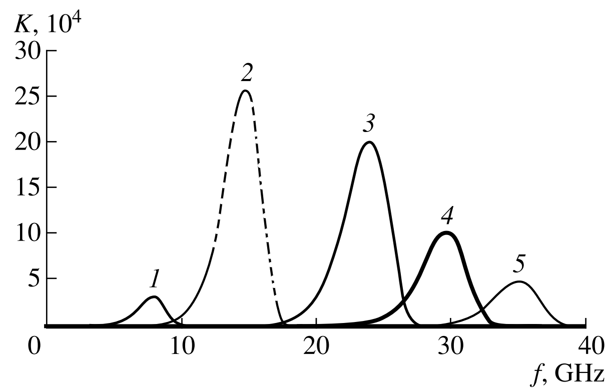

Fig. 5. Frequency dependences of the single-pass wave-power amplification coefficient calculated using linear theory for the parameters of the beam–plasma system presented in Section 2 at the plasma densities of n_p = (*1*) 8×10^{12}, (*2*) 2×10^{13}, (*3*) 4×10^{13}, (*4*) 5.5×10^{13}, and (*5*) 7×10^{13} cm^{-3}.

Figure 6c shows the theoretical dependence of the linear single-pass wave-power amplification coefficient on the plasma density for two input-signal frequencies: 9.1 GHz (curve *1*) and 12.9 GHz (curve *2*). A comparison of Figs. 3b, 6b, and 6c shows that the experimental results are in good agreement with the results of theoretical calculations. For both signal frequencies, the experimentally observed ranges of plasma densities in

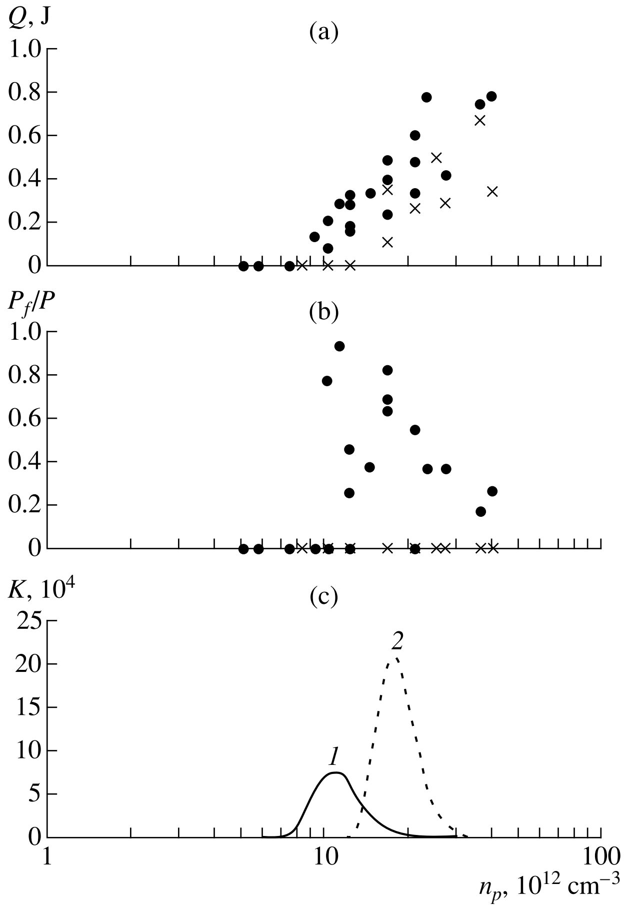

Fig. 6. (a) The output microwave radiation energy measured by the calorimeter as a function of the plasma density and (b) the ratio between the power measured by the narrowband and broadband receivers vs. the plasma density at t = 75 ns after applying the voltage pulse to the diode in the case when a 75-kW signal at a frequency of 12.9 GHz is fed to the entrance of the system (circles) and without an input signal (crosses); the microwave absorber is present. (c) Dependence of the linear single-pass wave-power amplification coefficient on the plasma density at f_0 = (*1*) 9.1 and (*2*) 12.9 GHz.

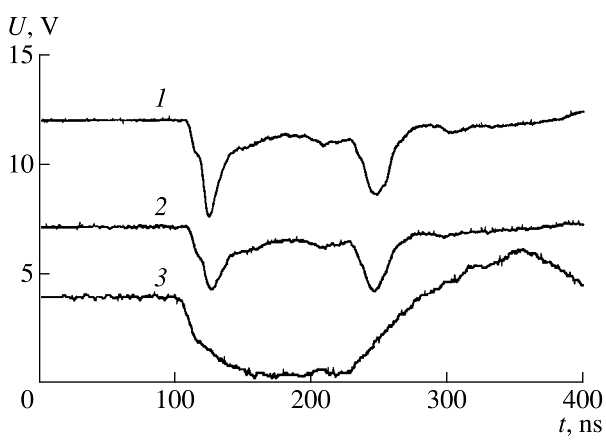

Fig. 7. Waveforms of the signals from (*1*) the broadband and (*2*) narrowband receivers and (*3*) the voltage pulse at the diode for f_0 = 9.1 GHz, P_{in} = 40 kW, and $n_p = 3 \times 10^{12}$ cm^{-3}; the microwave absorber is present.

which the system operates as an amplifier are in agreement with theoretical predictions. However, the theoretical and experimental threshold values of the density at which the system passes over to the amplification regime are different. This discrepancy can be explained by the inaccuracy of the measurements of the absolute values of the plasma density. We also note that it makes no sense to compare the experimental and calculated values of the amplification coefficient, because the presence of the microwave absorber in the system was ignored in calculations. It also follows from Fig. 6c that, according to the theory, there exists a range of plasma densities in which the amplification can take place for both frequencies of the input signal. In the experiment, at a plasma density of $n_p = 1.2 \times 10^{13}$ cm^{-3}, the beam–plasma system amplified the signal at frequencies of both 9.1 and 12.9 GHz.

It is also of interest to compare the experimental and theoretical dependences of the parameters of the amplification regime on the energy of REB electrons. According to the theory, for a given frequency of the input signal, the electron energy at which the amplification occurs increases with increasing the plasma density. Figure 7 shows the waveforms of the signals from the broadband (*1*) and narrowband (*2*) receivers and the voltage pulse at the diode (*3*). The figure corresponds to a plasma density of $n_p = 3 \times 10^{12}$ cm^{-3} and an input-signal frequency of f_0 = 9.1 GHz. It is seen from the figure that the amplification coefficient is maximum at the leading and trailing edges of the voltage pulse when the energy of the REB electrons is lower than the maximum energy. As the plasma density increases, the maximum value of the amplification coefficient shifts to the top of the voltage pulse, where the energy of REB electrons is maximum (Fig. 4a).

It is seen from Fig. 7 that, although the system operates in the amplification regime, the ratio between the signals from the narrowband and broadband receivers is below unity at the leading edge of the voltage pulse. It looks as if the spectrum of the output radiation is broader than 0.5 MHz. However, we believe that this effect may be attributed to an insufficiently fast response of the narrowband receiver, which cannot trace fast signals lasting several nanoseconds. The Q-factor of the microwave filter of the narrowband receiver is on the order of 20; consequently, the characteristic rise time of the signal is $t_0 = Q/f_0 \approx 2$ ns. In Fig. 7, the rise time of the first signal from the broadband receiver is ~5 ns, which is comparable with t_0. If the signal duration is much longer than 2 ns (as, e.g., in Fig. 4), then the narrowband receiver correctly reproduces the signal shape.

4. CONCLUSION

(i) A stable regime of amplification of a slow plasma wave in a beam–plasma system has been obtained for the first time. For a 9.1-GHz input signal, there exists a range of plasma densities in which the spectrum of the output microwave radiation lies in a 0.5-GHz-wide band throughout the entire voltage pulse at the diode. The output power of the amplified signal attains 8 MW, and the power amplification coefficient is on the order of 200. The experimentally measured range of plasma densities in which the amplification of a 9.1-GHz signal takes place agrees well with the results of calculations using linear theory.

(ii) It has been shown experimentally for the first time that the beam–plasma amplifier can operate at frequencies of 9.1 and 12.9 GHz. The range of plasma densities in which the amplification is observed agrees with the theoretical results. Moreover, the experiment confirms the theoretical prediction that there is a value of the plasma density at which the beam–plasma system can amplify signals at both frequencies.

(iii) The influence of the energy of REB electrons on the amplification band has been observed experimentally. The results obtained agree with theoretical predictions.

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