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Generation of ultra-short pulse sequences in crossed-field amplifier in self-excitation regime

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A W-band amplifier with crossed fields operating under dual-frequency self-excitation conditions has been studied. It is shown that the generated frequencies correspond to the edges of the system bandwidths, at which there is a significant increase in coupling resistance. It is shown that by applying an external signal at a frequency equal to the average value between the generated frequencies, regimes of generating sequences of ultrashort pulses with a duration of about 20 ps, a repetition period of about 100 ps, and a peak instantaneous power of more than 1 kW can be obtained.

Keywords: crossed-field amplifier, W-band, ultrashort pulses generation, dual-frequency self-excitation.

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Different options for generating powerful ultrashort pulses in the millimeter range are currently under consideration. For example, in [1], the generator design with passive mode synchronization based on a Ka-band gyroresonant amplifier with a saturable absorber in the feedback circuit was experimentally investigated. A new design of such a generator with two parallel emitting and absorbing electron beams is proposed in [2,3]. In [4], pulse sequences based on self- synchronization of modes in a K-band gyroresonant amplifier with a feedback circuit are experimentally obtained. In [5], the possibility of implementing a similar effect in Cherenkov-type traveling-wave tubes in the W-band is investigated. In [6–8] the method for generating pulse sequences based on the formation of solitons of self-induced transparency arising in the process of cyclotron-resonance interaction of electromagnetic pulses with initially rectilinear electron beams is discussed. It should also be noted that low-power pulses can be generated based on semiconductor electronics devices [9].

In this paper, the generation of ultrashort pulses in a W-band amplifier with crossed fields is investigated. This class of amplifiers has certain advantages over amplifiers of other types. In particular, compared to O-type amplifiers, there is no need to create a complex electron-optical system for focusing the electron beam in the fly-through channel, the typical dimensions of which decrease in proportion to the wavelength. In its turn, compared to gyroresonance-type amplifiers, there is no need to create strong magnetic fields for the formation of helical electron streams. Amplifiers with crossed fields are described by a fairly large output power in the centimeter range, which for pulsed devices can reach the values of tens and hundreds of kilowatts [10]. At the same time, there are obvious prospects for the creation of devices in the millimeter range, taking into account the success in the development of magnetron-type devices similar in design [11,12].

For spikes generation, we propose a scheme of amplifier operation in the self-excitation mode, in which two spectral components with commensurate amplitudes are present in the output signal. In its turn, an external signal is fed into the system at a frequency close to the average value of these frequencies. Simulation results show that the output signal may contain sequences of pulses whose peak radiated power is many times greater than the average radiated power.

Various types of slow-wave structures and their modifications are now known and investigated and can be applied in a crossed-field amplifier. In magnetrons of the millimeter wavelength range, multistage resonator systems are actively used, the depth of which is proportional to $\lambda/5$. Unlike single-stage systems, such systems have low dispersion at higher spatial harmonics and retain high values of coupling resistance [13].

The simulation of the interaction between the electron flux and the microwave signal was performed using the CST Studio Suite software package. The complete amplifier model is a cylindrical system (Fig. 1, a) consisting of a cathode of radius 1.15 mm and an anode of radius 1.5 mm. Unlike the amplitron, the magnetron-type amplifier contains a drift space in which the electrons are ungrouped, thus eliminating spurious electron flow feedback. The energy input and output of the decelerating system are also provided by means of matching elements. End shields are used on the cathode to localize the electron flow in the interaction space.

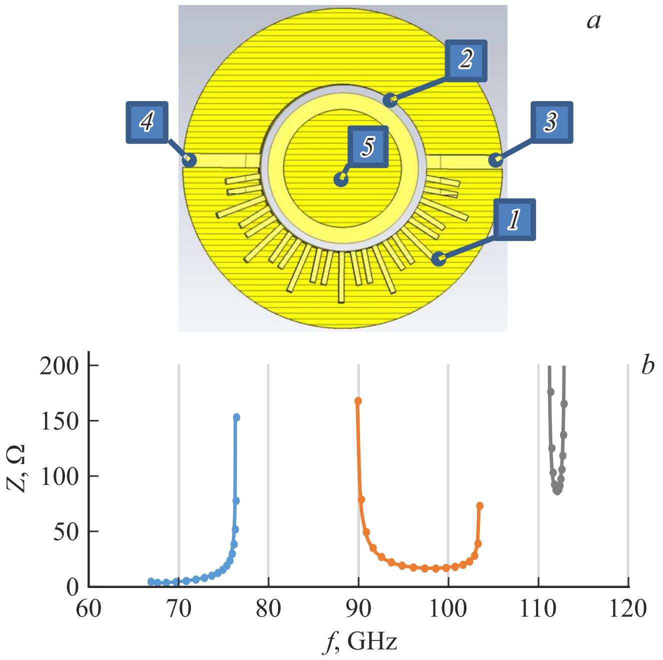

Figure 1. *a* — model of the amplifier under study: *1* — resonant cavity system, *2* — drift space, *3* and *4* — energy input and output, *5* — cathode. *b* — calculated values of coupling resistance as a function of frequency in first (*1*), second (*2*), and third (*3*) bandwidths.

The device under study uses a three-stage resonant cavity system, which is three rectangular cutouts, two short and one long (Fig. 1, *a*). As can be seen, in the second bandwidth $(+1)$ the spatial harmonic has low dispersion at sufficiently high values of coupling resistance (Fig. 1, *b*).

The operating harmonic is selected in the second bandwidth 90–100 GHz, which has a higher coupling impedance than the first bandwidth 65–77 GHz, and a wider bandwidth than the third bandwidth 111–113 GHz.

When selecting the parameters of the device operating mode, the synchronism condition can be fulfilled simultaneously for several bandwidths. In this case, the synchronism condition is observed to be fulfilled at the boundaries of the second and third bandwidths, which have an order of magnitude higher coupling resistance. Therefore, a two-frequency mode of generation at frequencies 90 and 111.1 GHz occurs in the system. Figure 2, *a* shows the time dependence of the relative intensity of the radiation and the spectrum of the output radiation in the self-excitation mode. The relative intensity was calculated by formula

$$I(t) = a(t)^2 / \langle a(t)^2 \rangle,$$

where $a(t)$ — the instantaneous value of the field amplitude, and the operation $\langle \ldots \rangle$ denotes averaging over the implementation time. The occurrence of dual-frequency generation can be explained as follows: at the edges of the bandwidth, the system has a strong dispersion and, as a consequence, a strong increase in coupling resistance. The high-frequency bandwidth has a coupling resistance several times greater than the operating harmonic. Therefore, it is impossible to harmonize the system in this frequency range, and the VSWR (voltage standing wave ratio) of the system in this range can reach values of 10 or more units. Thus, when the electron flow begins to interact with the slow-wave structure harmonics, there is a higher-frequency component near 110 GHz in addition to the operating frequency, which due to poor matching is locked in the system and continues to effectively take energy from the electrons. The same thing happens at a frequency near 90 GHz, which is located at the edge of the operating harmonic range, where the system is poorly matched.

When an external signal of power 100 W with frequency located in the center between the natural oscillation frequencies is introduced into this system, the system output produces a spike mode of generation associated with the mode synchronization effect (Fig. 2, *b*). Recall that the mode synchronization effect is manifested by the addition of phased oscillations with equidistant spectrum [14]. In the simplest case of three oscillations interaction

$$a_k(t) = a_0 \exp\bigl(i[(\omega + k\Delta\omega)t + \varphi_k]\bigr),$$

$k = -1, 0, 1$, under the condition of phased modes $\varphi_k = \varphi$ the total amplitude is written in the form

$$A(t) = \sum_k a_k(t) = a_0\, e^{i(\omega t + \varphi)} \bigl(2\cos(\Delta\omega t) + 1\bigr), \qquad (1)$$

and the total intensity is represented as

$$I(t) = \mathrm{Re}\bigl\{A(t)\bigr\}^2 = a_0^2 \bigl(2\cos(\Delta\omega t) + 1\bigr)^2 \cos^2(\omega t). \qquad (2)$$

According (2), in the total signal are formed uniformly spaced from other wave packets with peak intensity

$$I_{\max} = 9a_0^2 = 6\langle I(t)\rangle, \qquad (3)$$

where $\langle I(t)\rangle = 1.5a_0^2$ — average value of intensity calculated over the entire implementation.

From Fig. 2, *b* it can be seen that the maximum value of the pulse relative intensity reaches a value of about 6. The spikes duration is of the order of 20 ps with a repetition period of about 100 ps. The instantaneous oscillation power reaches values of about 1.4 kW, which corresponds to the peak value of the average power equal to 0.7 kW. The average oscillation power is about 0.24 kW. The obtained pulse sequences are characterized by a sufficiently high correlation coefficient between pulses, the value of which is about 0.96.

Among possible applications of powerful ultrashort pulses of millimeter range it is necessary to mention systems of nonlinear pulse spectroscopy, where an approach based on amplification of short microwave pulses of low power currently dominates. In this case, very complex and expensive klystrons with distributed interaction are used as amplifiers [15–17].

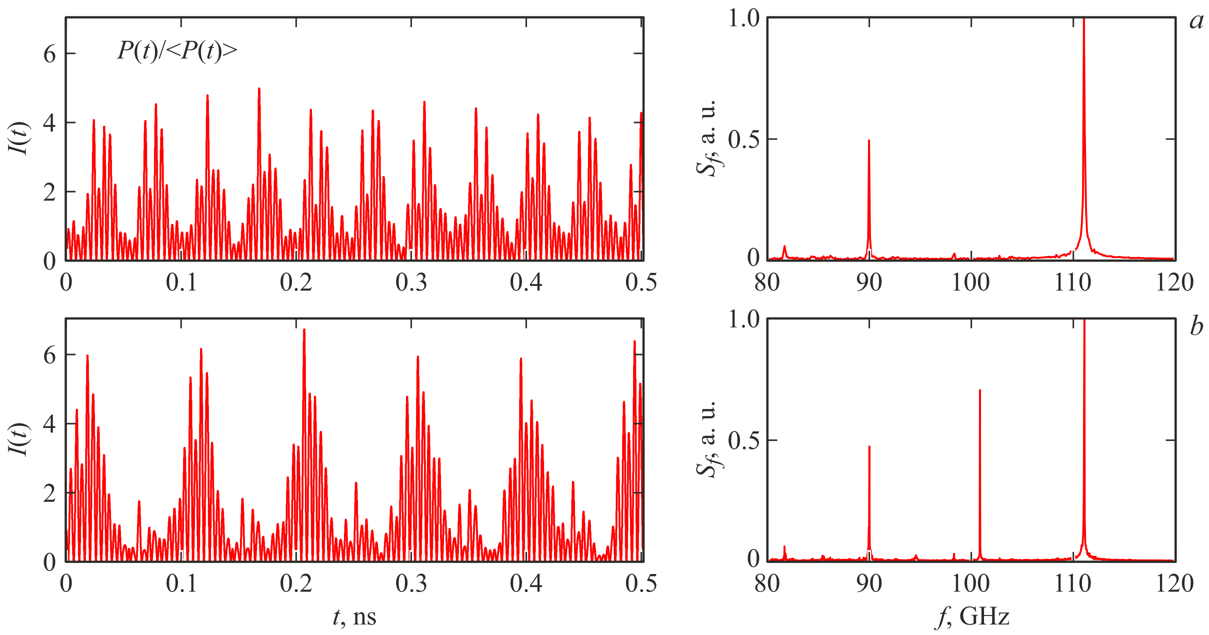

Figure 2. The time dependence of the relative intensity and the output emission spectrum in the self-excitation mode (a) and in the external signal mode (b).

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Conflict of interest

The authors declare that they have no conflict of interest.

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