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Generation of ultra-short correlated pulse sequences in a W-band travelling-wave tube with feedback circuit

© A.A. Ivanov[1,2], R.M. Rozental[1,2], D.A. Sidorov[1,3], A.V. Sukhoverkhii[3]

[1] Lobachevsky University of Nizhny Novgorod,
Nizhny Novgorod, Russia
[2] Federal Research Center A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences,
Nizhny Novgorod, Russia
[3] JSC SPE „Salyut", Nizhny Novgorod, Russia
E-mail: daniil_sidorov@mail.ru

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A W-band folded waveguide pulsed traveling-wave tube with feedback circuit, was experimentally investigated. Periodic sequences of correlated pulses with a duration of 400–500 ps with a peak power many times exceeding the average output radiation power were registered. The set of measured data allows us to identify this operating mode as self-mode-locking of several longitudinal modes of the system.

Keywords: travelling-wave-tube, ultra-short pulses generation, self-mode-locking.

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The generation of short high-power millimeter-range radiation pulses is relevant to a number of scientific problems. Of note here are radar applications, where shortening of pulses allows for an increase in spatial resolution [1], and several high-intensity spectroscopy applications [2,3]. One way to generate sequences of correlated ultra-short pulses is to use vacuum electronic amplifiers with a feedback circuit. The earliest designed generator of this kind was based on a traveling-wave tube (TWT) with a saturable absorber in the feedback circuit [4]. The absorber (called the expandor in the original paper) served to absorb signals with a low amplitude and transmit signals with a high amplitude, which provided an opportunity to maintain phasing of individual modes in the system. This approach was used in [5] to obtain sequences of ultra-short high-power pulses based on a Ka-band gyro-resonant TWT and a cyclotron saturable absorber. It was demonstrated in [6] that the generation of correlated sequences of ultra-short pulses is also possible in the model of a Cherenkov-type traveling-wave tube with delayed feedback. This effect is attributable to self-mode-locking, which ensures that output radiation consists of several equidistant frequencies with the same phase difference. Such generation regimes have been observed experimentally for the first time in [7] in a centimeter-range TWT with a helical slow-wave structure.

Significant progress is currently being made in the design of millimeter-wave TWTs. Specifically, the operation of devices with an output power of several hundred watts in the W band [8,9], more than ten watts in the 260 GHz range [10], and approximately one watt in the 340 GHz range [11] has been demonstrated experimentally. In Russia, the best results were obtained at AO NPP Salyut, where a family of pulsed W-band TWTs with an output power up to 50 W was designed [12,13]. The present study details the results of examination of such a TWT with a feedback circuit. A folded-waveguide slow-wave system featured approximately 60 periods positioned with a pitch of about 1 mm. The wave slowing factor in the operating frequency band varied from 4 to 5. The range of anode voltages U_a of the tube was 11.5–13.5 kV, and the beam current was set to 97 mA in experiments. With these parameters, the gain of the chosen TWT device was 30 dB.

The feedback circuit was formed by tapping off a fraction of the output signal at the level of -10 dB. The resulting signal was fed to the TWT input through an adjustable attenuator and a section of dielectric waveguide with a loss close to 2 dB in magnitude. A semiconductor detector with a minimum signal rise time no worse than 200 ps and a digital oscilloscope with a bandwidth of 5 GHz and a sampling rate of 20 GS/s were used to record the output signal envelope. The TWT was operated in the pulsed regime with an approximate pulse duration of 20 μs and an off-duty factor of 100. Figure 1, *a* shows a typical oscilloscope record of an anode voltage pulse.

When the feedback depth exceeded the value of -30 dB, stationary oscillations with an output power of approximately 20 W were excited in the system. As the feedback depth was reduced gradually, periodic self-modulation regimes, which transitioned to spike generation regimes with an average power of about 8 W, were excited. A typical complete oscilloscope record of signal $u(t)$ from the detector in this regime is shown in Fig. 1, *b*.

It is convenient to characterize spike regimes by relative radiation intensity $I(t)$, which indicates the value of instantaneous radiation power relative to the average level. Since the signal from the detector is proportional to the amplitude

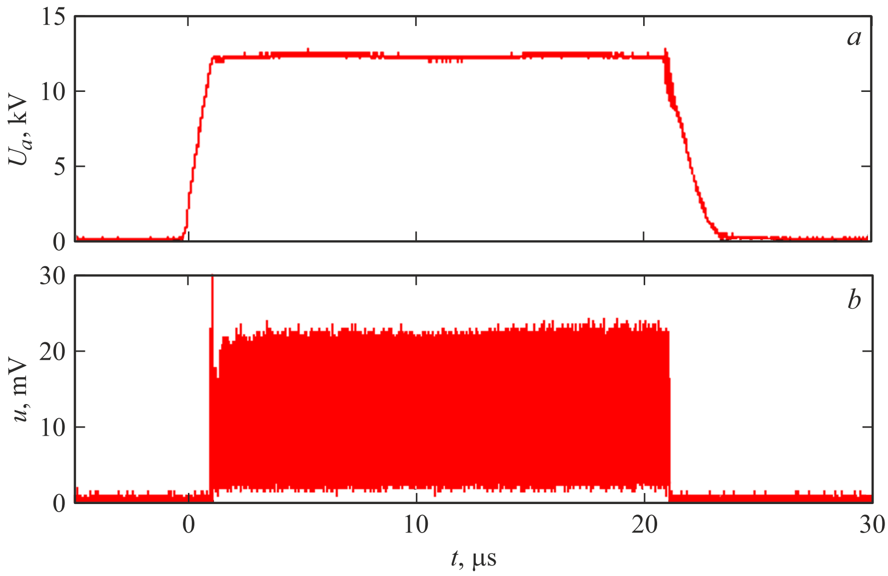

Figure 1. Typical oscilloscope records of an anode voltage pulse (a) and the output signal (b) in the regime of generation of ultra-short pulse sequences.

of incident radiation squared, the corresponding expression takes the form

$$I(t) = P(t)/\langle P(t)\rangle = u(t)/\langle u(t)\rangle, \quad (1)$$

where $P(t)$ is the instantaneous signal power value and angle brackets denote averaging over the complete duration of the signal. Figure 2, a presents the time dependences of relative intensity at an anode voltage of 12.8 and 13.06 kV and a feedback depth of -12 dB.

In the case of $U_a = 12.8$ kV, the duration of a single pulse measured at 1/2 of the maximum level was close to 500 ps, and the relative intensity reached a value of 3.6. At $U_a = 13.06$ kV, the pulse duration dropped to 400 ps, while the relative intensity increased to 7.5. The approximate pulse repetition period was 2.6 ns. The self-correlation function calculated for the obtained signals (Fig. 2, b) was used to determine the minimum coefficient of correlation between pulses $K_{\min}$. At $U_a = 12.8$ kV, this coefficient assumed a value of $K_{\min} = 0.978$; at $U_a = 13.06$ kV, $K_{\min} = 0.967$.

The observed regimes of generation of correlated pulse sequences may be interpreted as a regime of self-mode-locking. Such regimes in microwave devices based on electron fluxes have been characterized theoretically for the first time in [14] for a model of a free-electron laser with a high-Q cavity. It was later suggested that, since the equations used are universal in nature, the results reported in [14] should also be applicable to other types of electronic generators (in particular, to generators based on TWTs with delayed feedback [15]).

A set of conditions specifying the mode locking regime via output signal analysis was formulated in [6]. The first condition is the equidistant nature of the spectrum. It was satisfied in experiments with a fine degree of accuracy: the distance between adjacent frequency components of the signal envelope spectrum was 369.9 ± 0.1 MHz in the first case and 377.5 ± 0.1 MHz in the second case (Fig. 2, c). Both these values were close to the calculated distance between the longitudinal modes of the ring cavity formed by the TWT slow-wave structure and the feedback circuit. This distance varies within the interval of 370–400 MHz depending on the slowing factor.

The second condition is the proximity of the maximum relative intensity to the theoretical values. In the case of locking of three modes with the same amplitude, the maximum relative intensity is $I_{\max} = \max\{I(t)\} = 3$; with five modes, it increases to 6.25. The experimentally observed values exceed the theoretical estimates due to the fact that a large number of modes are involved in the locking process.

The third condition is the proximity of the minimum coefficient of correlation between pulses to a unit value, which was also fulfilled with fine accuracy.

The fourth and final condition is the proximity of duty factor D (the ratio of the pulse duration to the pulse repetition period) to the theoretical limit. In the case of locking of three and five modes, the theoretical value is $D \approx 0.3$ and $D \approx 0.2$, respectively. In experiments, the duty factor was $D \approx 0.2$ and $D \approx 0.15$ at $U_a = 12.8$ kV and $U_a = 13.06$ kV, respectively.

Taken together, these data allow us to identify the obtained generation regimes as self-mode-locking ones.

In conclusion, we note that the examined ultra-short pulse generator may be used as the source of an input signal for the W-band gyro-resonant amplifier under development at the Institute of Applied Physics [16]. According to theoretical estimates, it should be possible to produce ultra-short pulses with a power of hundreds of kilowatts in this scenario [17].

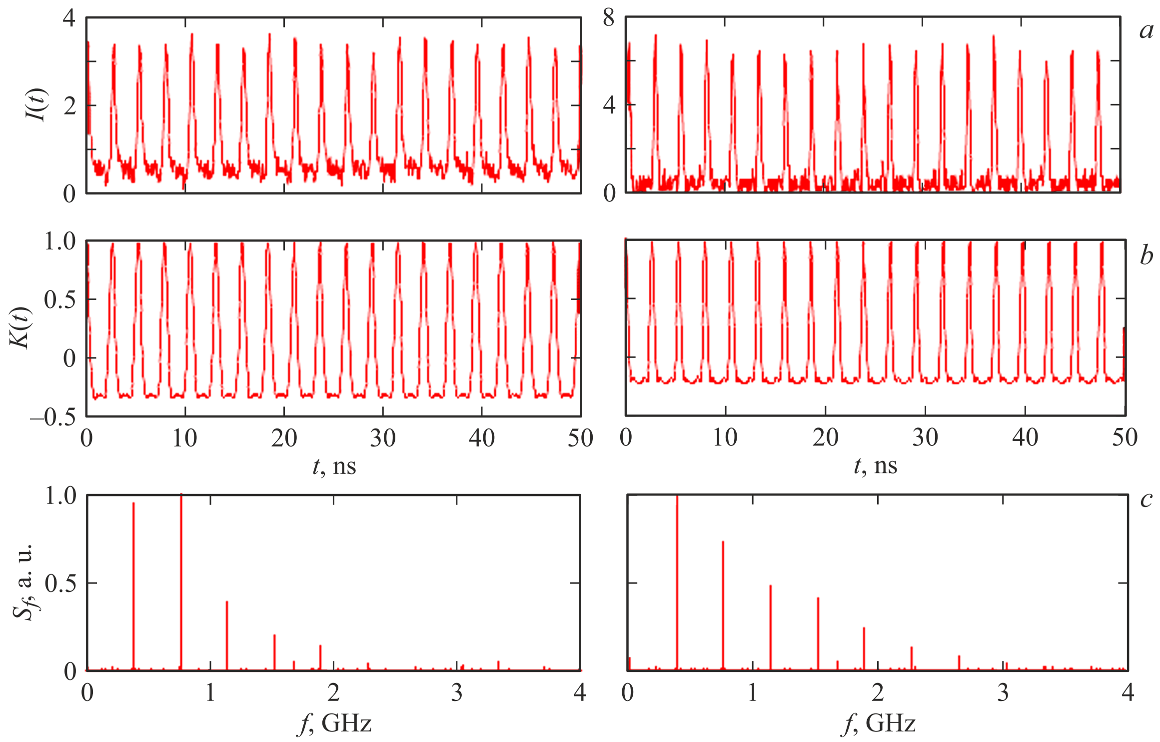

Figure 2. Oscilloscope records of the output signal (*a*), self-correlation functions (*b*), and spectrum of the envelope (*c*) in spike generation regimes at $U_a = 12.8$ kV (left column) and 13.06 kV (right column).

Conflict of interest

The authors declare that they have no conflict of interest.

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