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Generation of Dark Envelope Pulses in a Modified Noisetron Scheme

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The generation of dark envelope pulses with a duration of about ~ 10 ns is obtained in a modified noisetron circuit consisting of two nonlinear amplifiers: a multicavity drift klystron and a travel-ing wave tube (TWT), captured by a delayed feedback circuit. The drift klystron operates in the output power saturation mode, and the TWT amplifier operates in the nonlinear cross mode, in which there are two N-shaped sections on the amplitude characteristic of the lamp, and the phase shift dependence on the signal power at the traveling wave tube entrance is highly nonlinear. It is shown that an increase in the chaotic signal power in a ring leads not only to a decrease in the average repetition period of dark envelope pulses, but also to the formation of bound states of dark and anti-dark envelope pulses.

Keywords: dissipative solitons, noisetron, TWT, klystron.

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The construction of sources of short and ultrashort envelope pulses is a currently relevant issue in microwave electronics. Such pulses have potential applications in the study of high-speed processes and processing of various materials and biological tissues [1], and their bound states (e.g., „light“ and „dark“ pulses) may be used in data transmission systems as extended data bits [2]. Nonlinear optics techniques (passive mode locking with a saturable absorber [3,4] or amplifier [5]), passive mode locking with a Kerr-type nonlinearity [6,7], nonlinear parametric processes [8], etc.) are used to generate short nonlinear envelope pulses in the microwave range with durations ranging from several hundred picoseconds [4,5] to several nanoseconds [8] or tens of nanoseconds [3,6,7]. Light and dark envelope pulses are distinguished among the nonlinear pulses (dissipative envelope solitons) forming in media/systems with amplification and dissipation [9]. The former ones are formed from system noise and have the shape of a bell [3,4,6,8]. Dark pulses, on the contrary, form as narrow „dips“against an amplitude background [5,7]. It was proposed in [5] to use two nonlinear elements in the feedback circuit of a microwave active ring resonator to produce short dark envelope pulses of a subnanosecond duration. One of them (ferromagnetic film) supported three-wave parametric decay of a dipole magnetostatic surface wave into short exchange spin waves, thus inducing signal chaotization in the ring, while the other (transistor amplifier) was operated in the maximum output power mode (saturation mode) and limited the growth of amplitude of the chaotic signal.

The method for generation of short chaotic dark envelope pulses proposed in [5] may also be implemented in vacuum microwave generator circuits. A „noisetron“ [10] consisting of two traveling-wave tubes (TWTs) with a delayed feedback loop placed around them is the best known and, probably, one of the earliest chaos generators. One of these TWTs is operated in the linear amplification mode (linear amplifier), and the other is operated within the „falling“ section of the amplitude characteristic under strong phase nonlinearity (nonlinear amplifier). Wideband chaotic microwave signals have been generated successfully with the use of a noisetron in both centimeter [10] and millimeter [11] wavelength ranges. It was demonstrated in [12] that the substitution of two TWTs in a noisetron with two (linear and nonlinear) drift klystrons provides an opportunity to generate single sequences of light envelope pulses of a „giant“ amplitude with a duration on the order of several tens of nanoseconds. However, no modifications of a noisetron with two nonlinear microwave amplifiers have been proposed.

In the present study, a modified noisetron circuit for generation of dark envelope pulses is discussed. This noisetron consists of two vacuum microwave amplifiers. One of them (TWT), operated in strongly nonlinear and bistable modes, provides signal chaotization in a ring and induces instability of signal generation, while the other amplifier (drift klystron), operated in the maximum output power mode, limits the growth of amplitude of the chaotic signal and filters it.

Figure 1, a shows the modified noisetron circuit with a TWT amplifier, which is constructed using a single-section spiral slow-wave structure with a variable pitch for the 2–4 GHz frequency range, and a five-cavity medium-power KU-134E drift klystron with center frequency $f_0 = 2797$ MHz. The input and output of both vacuum amplifiers are connected in series to each other, and a delayed feedback loop is placed around them. The signal power level at the drift klystron input may be regulated with the use of an adjustable attenuator. A total of 90% of the signal power from the TWT amplifier output

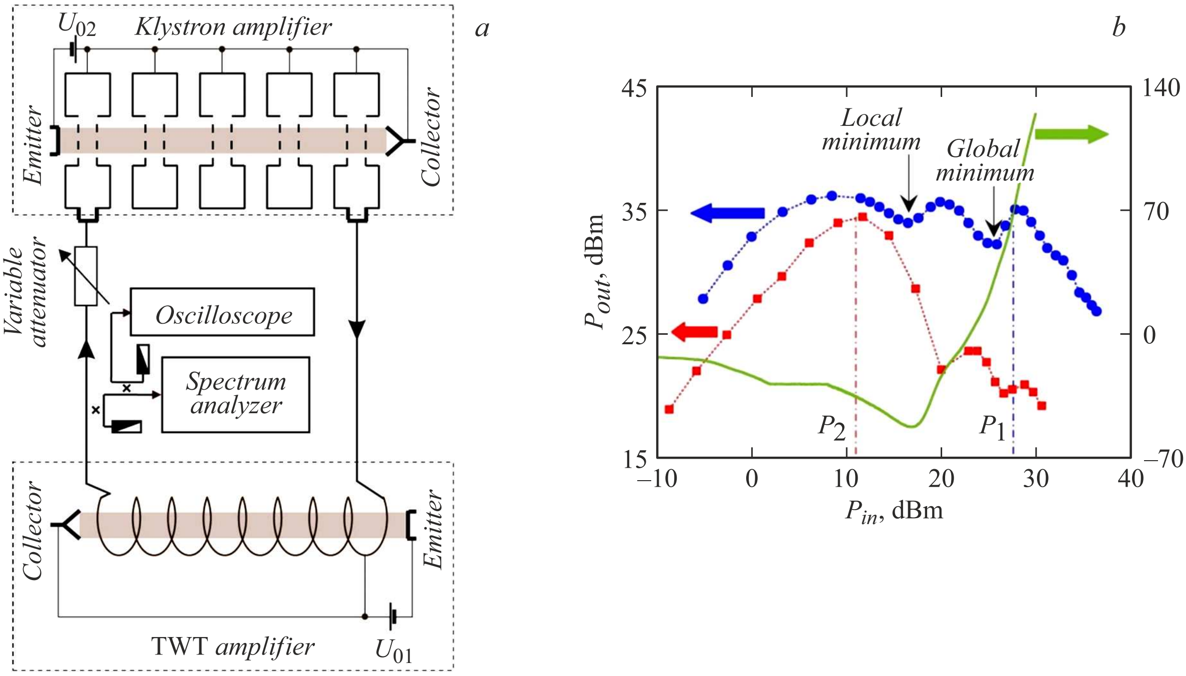

Figure 1. *a* — Schematic diagram of the microwave vacuum self-excited generator of chaotic dark envelope pulses; *b* — amplitude characteristic of the TWT amplifier (circles) and the drift klystron (squares) and phase characteristic of the TWT amplifier (solid curve) measured at frequency f_0.

are fed back into the ring, and the remaining 10% are sent via a directional coupler to the inputs of an E4408B spectrum analyzer and an Infiniium DSO81004B real-time oscilloscope for analysis and subsequent processing. The bandwidth of the real-time oscilloscope is 10 GHz. A signal sampling rate of 20 GS/s is set to analyze time series. The corresponding memory depth is 2 million points.

Figure 1, *b* shows the amplitude characteristic of the TWT amplifier and the five-cavity drift klystron and the dependence of signal phase shift on the signal power level at the TWT input measured at frequency f_0. The amplitude and phase characteristics of the TWT amplifier were determined at beam current $I_{01} = 50$ mA and accelerating voltage $U_{01} = 2500$ V, while the amplitude characteristic of the drift klystron was measured at beam current $I_{02} = 36$ mA and accelerating voltage $U_{02} = 2300$ V. It follows from the data presented in Fig. 1, *b* that the amplitude characteristic of the TWT amplifier features two N-shaped sections, which emerge due to the fact that the TWT operates in the nonlinear cross mode under normalized input power level $P_{in}/P_{01} \gg 10^{-5}$, where $P_{01} = I_{01}U_{01}$. This operation mode is specific in that the mean electron flux velocity varies due to an increase in the amplitude of an electromagnetic wave propagating along the slow-wave structure. The mean electron flux velocity increases and decreases in turns, remaining above the phase velocity of the electromagnetic wave. This electron flux behavior is the reason why minima and maxima emerge in the TWT amplitude characteristic. In addition, the phase shift of the microwave signal undergoes a change on the order of π in the cross mode. The dash-and-dot lines in Fig. 1, *b* denote the levels of P_{in} at the input of the TWT amplifier (P_1) and the drift klystron (P_2) at which dark envelope pulses are produced in the self-excited generator with these microwave amplifiers. It can be seen that the TWT operates within the rising part of the second N-shaped section of the amplitude characteristic (strongly nonlinear mode), while the drift klystron is operated in the maximum output power mode (weakly nonlinear mode).

The modes of signal generation in the modified noisetron circuit were switched by adjusting the beam current of the drift klystron; as is known [13], the klystron gain increases with increasing beam current magnitude. The other parameters of microwave amplifiers (klystron voltage and TWT voltage and beam current) remained unchanged. A monochromatic microwave signal was generated with the drift klystron and the TWT amplifier operating in the linear amplification mode and the strongly nonlinear mode, respectively, at $I_{02} = 23$ mA at the frequency of the dominant ring mode corresponding to frequency f_0. When the klystron beam current increased further, a transition to chaos via the known signal modulation mechanisms (frequency and amplitude) was observed [14]. The TWT amplifier and the drift klystron then continued operating in the strongly nonlinear mode and the linear amplification mode.

Figure 2 presents the spectral and temporal characteristics of the microwave signal obtained at klystron beam current $I_{02} = 34.5$ mA (i.e., when the intermittency mode was established). Although the signal power spectrum is noise-like in this case, it contains quasi-periodically recurring

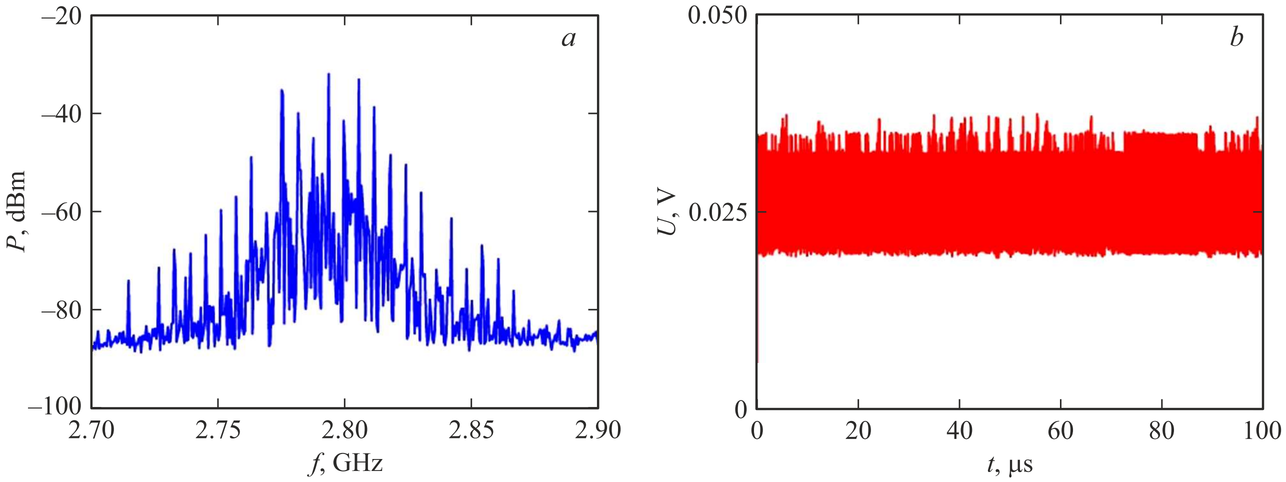

Figure 2. Power spectrum of the microwave signal (a) and its envelope (b) measured for beam current $I_{02} = 34.5\,\mathrm{mA}$ of the drift klystron.

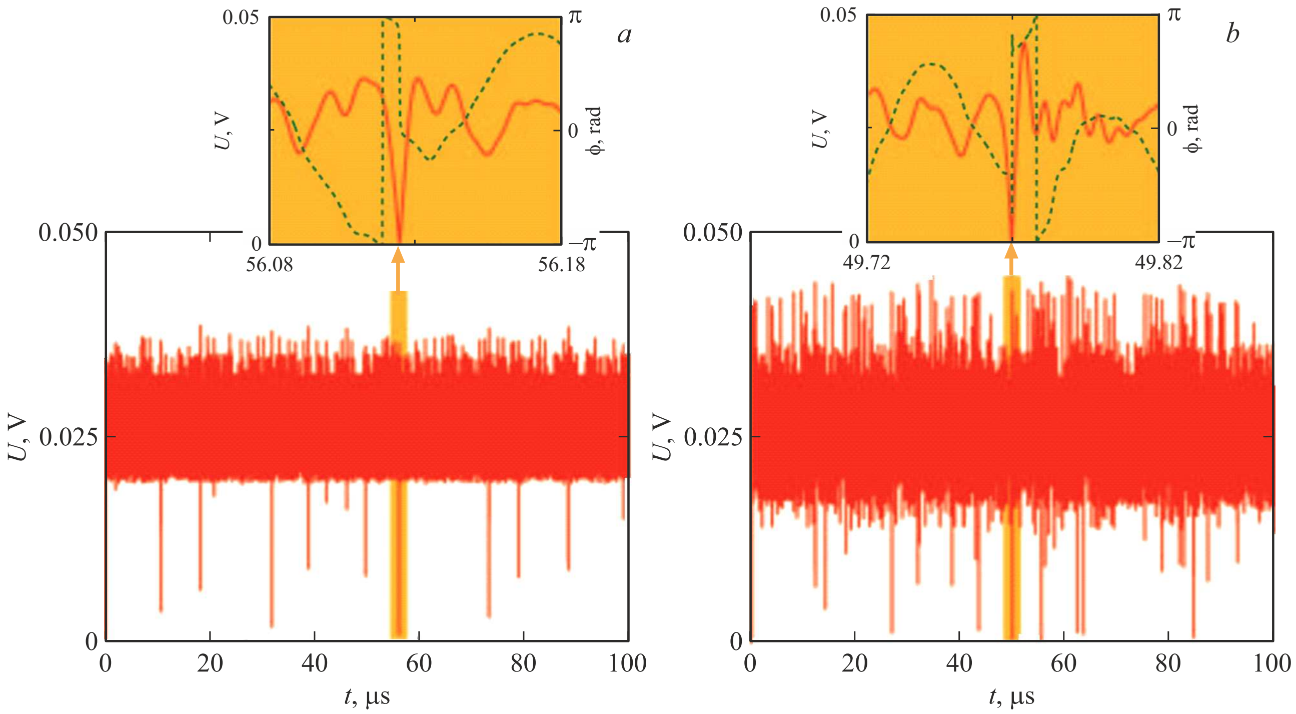

Figure 3. Time series measured for two values of the drift klystron beam current: $I_{02} = 36$ (a) and $45\,\mathrm{mA}$ (b). The corresponding enlarged fragments of dark envelope pulses are shown in the insets.

isolated spectral components that are unstable in time. These features in the spectral characteristic are related to intervals in the time domain where either chaotic or quasi-periodic variation of the envelope with time is observed.

Fundamental changes in the chaotic dynamics of the system are initiated at $I_{02} = 36\,\mathrm{mA}$ (Fig. 3, a) when the integral chaotic signal power at the TWT amplifier input corresponds to P_1 and the signal power at the drift klystron input corresponds to P_2 (Fig. 1, b). It follows from the data presented in Fig. 3, a that the intermittency mode is superseded by the mode of generation of isolated narrow dips (dark envelope pulses) against a chaotic amplitude background. The enlarged fragment of amplitude and phase profiles of one such dip is shown in the inset of Fig. 3, a. It is evident that these profiles are consistent with amplitude and phase profiles of a dissipative dark envelope soliton (the amplitude profile is symmetric, while the phase within it jumps by $\sim \pi$). The obtained dark pulses have duration $T_d \cong 10\,\mathrm{ns}$, which is specified by time of flight $\tau = l/v_0 = 10.9\,\mathrm{ns}$ of an electron beam along the TWT slow-wave structure ($l = 32.3$ cm is the slow-wave structure length, $\upsilon_0 = \sqrt{2U_{01}e/m}$ is the initial electron velocity, and e and m are the charge and the rest mass of an electron), and repetition period averaged over the realization length $T_r \cong 7.4\,\mu$s, which is governed by the nonlinear interaction of the multifrequency microwave signal with an electron beam in the TWT. The algorithm for calculation of the phase of the microwave signal envelope is based on the Hilbert transform and was discussed in detail in [13].

When the klystron beam current was increased further to $I_{02} = 45$ mA (Fig. $3, b$), the averaged period of dark envelope pulses dropped to $T_r \cong 3.1\,\mu$s and „spikes" in the form of anti-dark envelope pulses emerged. These spikes differ from light envelope pulses in that their amplitude drops to the amplitude background level instead of the noise level. In addition, their amplitude increases with the signal power level at the TWT amplifier input. If one examines the enlarged fragment of time realization (inset in Fig. $3, b$) in detail, the bound state of dark and anti-dark envelope pulses, which have amplitude and phase profiles similar to those of bound dark and anti-dark envelope solitons, becomes evident. The existence of the latter has been predicted theoretically for bistable dispersive nonlinear media [15]. The presence of several N-shaped sections in the TWT amplitude characteristic is indicative of bistability in the examined distributed active ring resonator. The emergence of time dispersion is attributable to the fact that the multicavity drift klystron has characteristic (resonance) frequencies [13].

In our view, the generation of dark envelope pulses is induced by the suppression of generation of a chaotic microwave signal due to a change in both amplitude conditions (owing to a reduction in the gain of the drift klystron) and phase conditions (owing to a strong TWT phase nonlinearity) in the ring resonator. Thus, amplitude conditions for reinstatement of generation of a chaotic microwave signal will be defined by a combination of a low TWT gain value, which corresponds to a global minimum in the TWT amplitude characteristic, and a maximum gain of the drift klystron, which corresponds to the linear section of the klystron amplitude characteristic. Two (local and global) minima in the TWT amplitude characteristic are involved in the production of bound states in the form of dark and anti-dark envelope pulses. By analogy with the bistable „double-well" system characterized in [15], anti-dark envelope pulses are formed near a local minimum, where the TWT gain is higher, and dark envelope pulses are produced near a global minimum, where the TWT gain is lower.

We note in conclusion that the duration of chaotic dark envelope pulses depends linearly on the slow-wave structure length and may reach several nanoseconds in the X band. The obtained results are of interest in terms of development of nonlinear dynamics methods for generation of short pulses in vacuum circuits of both centimeter and millimeter (or even submillimeter) wavelength ranges.

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Conflict of interest

The authors declare that they have no conflict of interest.

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