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Increasing the efficiency of converting the energy of a high-voltage pulse into the energy of a microwave pulse of a nonlinear transmission line in a scheme with its reuse for exciting high-frequency oscillations

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A method has been implemented for generating two microwave-radiation pulses by using saturated-ferrite-based nonlinear transmission lines (NLTLs) sequentially excited by a single high-voltage pulse. Using the energy of a single video pulse to excite oscillations in two NLTLs allows increasing up to twice the efficiency of converting its energy into energy of high-frequency oscillations. This generation technique can provide emission of a sequence of microwave pulses with repetition rate of tens of MHz.

Keywords: nonlinear transmission lines, microwave pulse sequence, high efficiency, high pulse repetition rate.

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Development of methods for generating nanosecond microwave-radiation pulses with the peak power amplitude exceeding 100 MW remains up to now an urgent trend in the field of high-current electronics [1]. One of the most important tasks in developing high-power microwave-electronics devices is increasing their energy efficiency [2]. Generators of high-power nanosecond microwave pulses may be divided into two groups. The first group is generators exploiting free electron flows [3,4]. Such generators are characterized by sub-gigawatt and gigawatt levels of the peak power and, as a rule, by a narrow-band spectrum of generated radiation. Among the main features of the electron-beam generators, there may be emphasized the fact that their operation needs high vacuum and creation of strong magnetic fields necessary to transport the beam; in addition, protection against accompanying X-ray radiation is needed. As an alternative (second) group, there may be regarded devices without electron beams: ultra-broadband systems and non-linear transmission lines (NLTLs). Among the devices of high-power microwave electronics there are NLTLs with saturated ferrite whose emission spectrum is broad and power characteristics amount to hundreds of megawatts in the decimeter wavelength range [5]. Conventional broadband radiation sources are based on a different approach which implies excitation of a broadband antenna by a monopolar or bipolar voltage pulse several nanoseconds in duration [6,7].

Using the NLTL-based generators in the sources of broadband pulses seems now promising because, unlike conventional microwave devices involving electron beams, the NLTL-based generators may be fully solid-state. The total energy efficiency of nanosecond microwave radiation sources combine the following factors: the efficiency of high-voltage pulse formation, energy necessary for creating strong magnetic fields, efficiency of converting the high-voltage pulse energy into the microwave pulse energy, and radiation losses. Today, NLTLs do not need additional power supplies to create the necessary magnetic fields, since a high-frequency oscillation circuit in NLTL with saturated ferrite has recently been successfully constructed by using permanent magnets instead of an external solenoid [8,9]. The decision to use permanent magnets allowed significant improvement of the generatorsẃeight-and-size characteristics and increase in their overall energy efficiency.

Energy efficiency in the case of the voltage-pulse energy conversion into high-frequency oscillations in NLTL does not exceed 10% even in the optimal operating modes of the generators. There exist a number of physical restrictions on the energy of the generated microwave pulse. Theoretical estimation shows that the maximum amplitude of oscillations is limited by the processes taking place during pulsed remagnetization of the saturated ferrite [10]. The existence of the transmission line dispersive and dissipative properties which cause the wave packet spread over lengths of about a meter prevents further increase in the peak power of high-frequency oscillations. The presence of dielectric losses in ferrites imposes in experiments extra restrictions on the optimal length of generators based on ferrite-containing NLTLs.

An increase in the energy efficiency of generators based on NLTLs with ferrite can be provided by selecting optimal duration of the high-voltage pulse exciting high-frequency oscillations. In the case when the high-voltage pulse duration is less than that of the excited oscillations and its top shape does not exhibit a constant-voltage section, the experiments demonstrate a decrease in the efficiency of generated radio pulses [11,12]. Energy efficiency of the generation process may be also significantly increased by using microwave ferrites and ferrites developed specially for NLTLs [13–15]. This paper presents the results of developing such a circuit for generating microwave pulses in NLTLs with saturated ferrite, which enables increasing

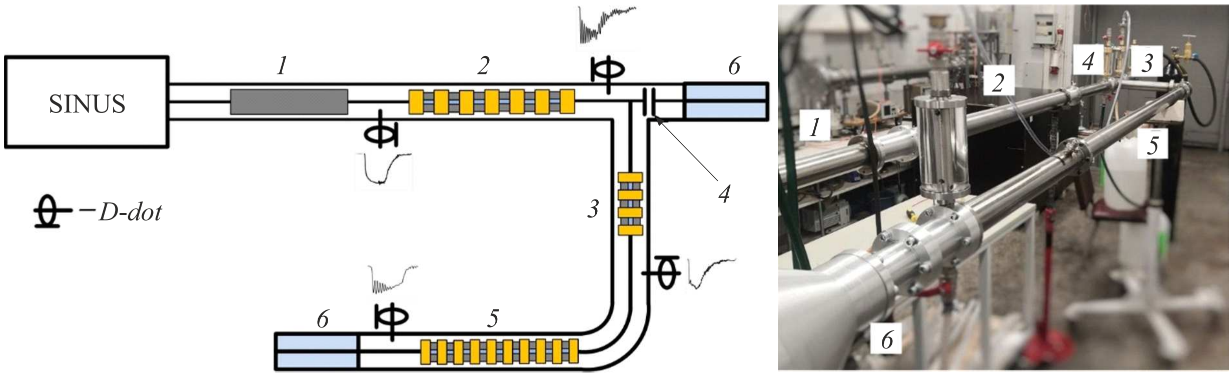

Figure 1. Experimental setup with two NLTLs. *1* — voltage pulse front sharpener based on an NLTL segment uniformly filled with ferrite, *2* — NLTL 1 with a corrugated central conductor, *3* — lowpass filter, *4* — highpass filter, *5* — NLTL 2 with a corrugated center conductor, *6* — matched coaxial broadband load.

the efficiency of the voltage-pulse energy conversion into high-frequency oscillations with reusing the incident voltage pulse to excite another NLTL.

Voltage pulse at the NLTL output is a video pulse modulated by high-frequency (several gigahertz) oscillations. To ensure high-frequency pulse emission from the NLTL outlet into the open space, in front of the broadband antenna there are typically mounted special T-joints comprising high— and low-pass filters and, in addition, a matched resistive load. The highfrequency component of the voltage pulse passes into the T-joint part accommodating the high-pass filter which is a capacitive element; after that, the pulse is emitted by the antenna. The remaining part of the pulse, which is a video pulse, passes into the T-joint part where the low-pass filter is located and is then absorbed in the load. Typically, the remaining video pulse retains at least half of the initial pulse energy.

In this work we have implemented a circuit where the remaining part of the video pulse is used to excite high-frequency oscillations in another saturated-ferrite-based NLTL located immediately after the high-pass filter.

High-frequency pulses were generated by using nonlinear transmission lines with ferrite and permanent magnets; their internal conductors had the form of corrugated structures. High-frequency oscillations get excited in the line during the subnanosecond shock front propagation in the transmission line possessing dispersive properties. In the case of corrugated NLTL geometry, the dispersion properties are determined by the discrete structure of the internal conductor and existence of capacitive coupling between adjacent of transmission line cells. The NLTL technology with a corrugated internal conductor is described in more detail in [8,9].

Layout of the experimental setup with two NLTLs is given in Fig. 1.

A high-voltage pulse from the SINUS generator [16] gets sharpened in NLTL uniformly filled with ferrite; the high-voltage pulse front length decreases from 3 to 1 ns. After sharpening, the voltage pulse enters NLTL 1. The high-frequency component of the NLTL 1 output pulse passes filter *4* and is absorbed in matched load *6*. The video pulse remaining part is fed into NLTL 2 through filter *3*. At the output of the second nonlinear transmission line, the modulated high-voltage pulse is completely absorbed in the matched load. Design of the coaxial broadband load is described in detail in [17]. In this work we exploited as NLTLs generating high-frequency pulses two different NLTLs 30 Ω in impedance operating in different generation-frequency ranges: NLTL 1 in the range of 0.7–1.1 GHz, NLTL 2 in the range of 1.25–1.7 GHz. Detailed description of these nonlinear transmission lines is given in [9]. Along with low-pass filter *3* there was located a section of corrugated NLTL which provided additional sharpening of the front of the remaining video pulse part. In the experiment, voltage pulses were detected with the *D*-dot sensors whose arrangement is shown in Fig 1. Fig. 2 demonstrates the recorded pulses

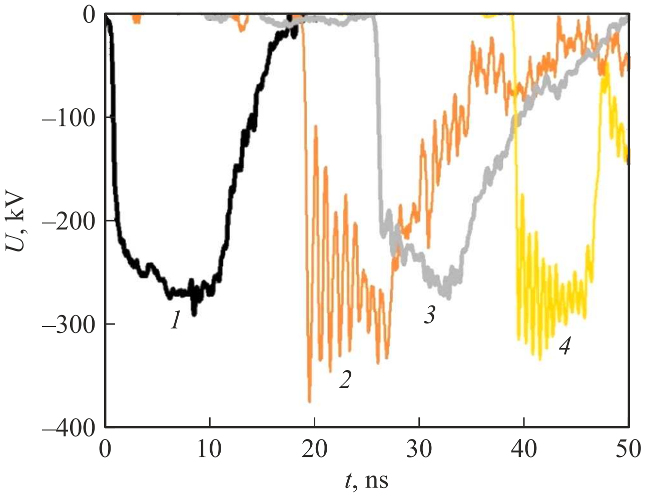

Figure 2. Voltage pulses in the order of passing through the system of gyromagnetic lines. *1* — voltage pulse after sharpening at the NLTL 1 input; *2* — voltage pulse at the NLTL 1 output; *3* — voltage pulse at the low-pass filter output; *4* — voltage pulse at the NLTL 2 output.

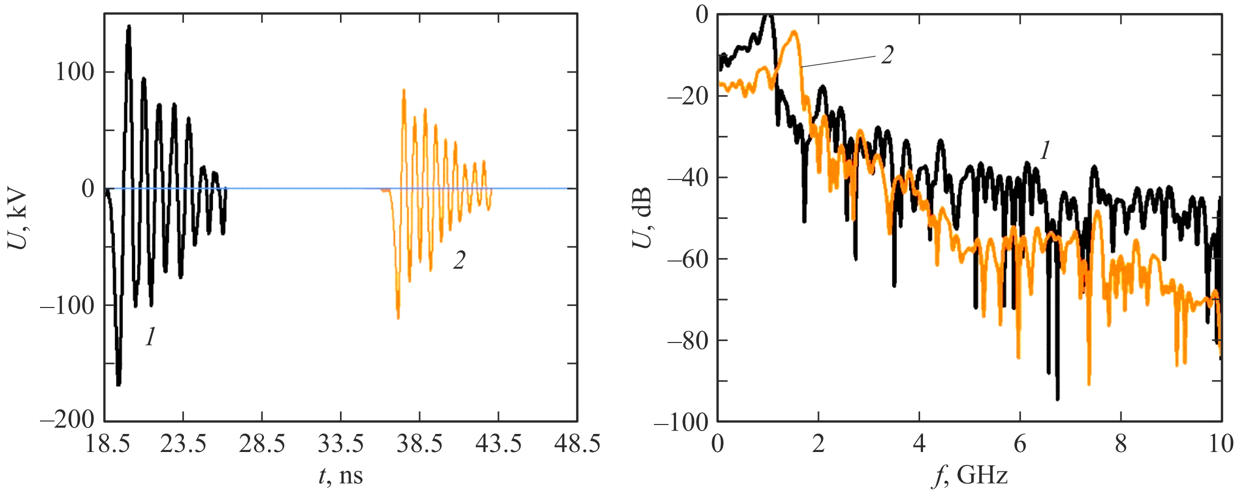

Figure 3. Radiofrequency pulses in the order of passing through the system at the incident pulse voltage of 293 kV, and their spectra. *1* — NLTL 1 pulse; *2* — NLTL 2 pulse.

in the order of passing through the system of gyromagnetic lines for the incident voltage pulse amplitude of $\sim$ 290 kV.

The interpulse delay is governed by the electrical length of the coaxial line sections between the measurement points.

Reflections from the high-pass filter are superimposed on the pulse tail *2* because this section has failed to be properly matched; overlap of these reflections with the main high-frequency pulse was prevented due to time decoupling in the measurement circuit. In the experiment, time decoupling allowed recording a pulse up to 8 ns long without overlapping with reflections.

In this study, microwave pulses after the filter were not detected directly because of specificity of the experiment design. Microwave pulses filtered by a digital filter (pulses *2* and *4* in Fig. 2), as well as their spectra, are presented in Fig. 3.

The maximum performance efficiency of the system was observed at the incident pulse voltage of $\sim$ 290 kV. Further increase in voltage was restricted by the system electrical strength. Design energy of high-frequency pulse oscillations *1* was 1.1 J, while that of pulse *2* was 0.25 J. Thereat, energy of the voltage pulse incident on the gyromagnetic line 1 was 27.5 J. Hence, the gyromagnetic line 1 energy efficiency is 4%, while that of two series-connected lines is 4.9%.

Notice that the efficiency of the single-line energy conversion is low because initially an excessively long pulse was used in the experiment. The experimental results show that, after generating a microwave pulse in NLTL 1, the voltage pulse duration decreases by 4 ns and the pulse itself loses energy of about 10 J.

This circuit may be applied practically provided the circuit employs, instead of loads, antennas emitting microwave pulses into the open space. The number of NLTLs may be increased; it depends on the initial voltage pulse duration and pulse duration that gets lost as a result of generation of high-frequency pulses in one NLTL. The circuit can involve both identical NLTLs and NLTLs with different operating frequencies. As a result, this circuit emits a short sequence of high-frequency pulses (three to five pulses) with the estimated repetition rate of 50 MHz.

Thus, this paper proposes for the first time a scheme for increasing the efficiency of converting the video-pulse energy into that of microwave pulses with reusing the energy of the constant component of the NLTL output pulse. The performance ability of the proposed circuit is demonstrated. In the experiments, the efficiency increase from 4 to 5% was achieved. This value may appear to be even higher in the circuit with two identical NLTLs. The result of developing this circuit may be implementation of a source of a short sequence of high-frequency pulses with repetition rate of about 50 MHz..

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Conflict of interests

The authors declare that they have no conflict of interests.

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