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Parameters of sub-gigahertz microwave signal transmission through a nanosecond GaAs-based photoconductive semiconductor switch

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Received November 7, 2025
Revised December 4, 2025
Accepted December 5, 2025

An experimental study of the transmission of a sub-gigahertz microwave signal in traveling wave mode through a photoconductive semiconductor switch in nonlinear amplification mode has been conducted. It was found that the formation of strong field domains in the switch does not significantly exacerbate the transmitted kilowatt microwave signal (~ 172 MHz) when absorbed in a matched and short-circuited load with a decrease in the amplitude of the microwave signal from 733 to 598 V and from 463 to 342.5 V, respectively. The use of a 42 mΩ short-circuit load leads to signal distortion, but it allows you to get a signal with a transition through zero. The results obtained demonstrate the possibility of using a photoconductive semiconductor switch for high-power pulsed microwave devices at high frequencies.

Keywords: PCSS, GaAs, Microwave, CFD.

DOI: 10.61011/TPL.2026.04.63196.20563

The use of semiconductor switches in high-power resonant microwave compressors provides an opportunity to construct highly stable devices with a long service life. For example, the generation of a microwave pulse with 12 $p-i-n$ diodes with a pulse power exceeding one kilowatt was demonstrated in [1]. The use of laser-controlled photoconductive semiconductor switches (PCSSs) in parallel connection will potentially increase switching power to gigawatt levels, which is comparable to the power of arrester-based solutions. An important advantage is the capacity of PCSSs to operate in a nonlinear mode with a low control optical energy of several tens of nanojoules and lock-on conductivity after the end of the control pulse when the electric field strength exceeds the threshold value. This mode is observed in gallium arsenide (GaAs) and is explained by the mechanism of collapsing field domains (CFDs) [2]. It is based on the generation of narrow Gunn domains at a terahertz frequency with a field stronger than 600 kV/cm and a negative differential mobility, which support avalanche generation of nonequilibrium electron-hole plasma with a filament density of 10 MA/cm. However, no experimental studies focused on the influence of CFDs on the passage of a high-power microwave signal through a closed PCSS in a nonlinear mode have been published yet. This is the reason why the present study was aimed at experimental evaluation of the possibility of transmitting a sub-gigahertz microwave signal through a high-voltage nanosecond photoconductive switch based on GaAs.

A sample with an operating voltage of 32 kV based on semi-insulating GaAs prepared by acceptor doping (Cr) was used in the experiment. It was designed as a crystal with a $p-i-n$ structure, where the i region had a resistivity of $10^9\,\Omega \cdot \mathrm{cm}$ and the p and n regions were formed under the contacts via diffusion of silicon and zinc. Ohmic contacts of the AuGe crystal were glued to gold contacts (films) on the surface of polycor VK-100-1. The contacts were positioned at the edges of a rectangular window 8.5×11 mm in size, which is used for laser irradiation of the interelectrode gap (9.5 mm) corresponding to the i region. The switch was mounted in a gap of the central conductor of a coaxial-planar waveguide chamber with an impedance equal to that of the coaxial path ($50\,\Omega$). The experiment with the sample requires simultaneous influences for switching the PCSS to the conducting state and forming a test microwave signal. The corresponding diagram is shown in Fig. 1. It consists of the PCSS switching circuit and the circuit for generating a test bipolar microwave signal (dotted line [3]) based on avalanche S diodes operating according to the CFD mechanism [4,5]. Both circuits are synchronized by control signals from the control board in modulator *3* by adjusting the time delay with an accuracy of 10 ns.

The circuit is actuated by charging an NKRFA07800 feeder (*4* in Fig. 1) with a length of 4.5 m from high-voltage modulator *3* by a bell-shaped signal with a duration of 250 ns and a maximum amplitude of approximately 16 kV. The waveguide chamber with the closed PCSS is connected to the other end of the feeder. Switch is opened by firing laser *1* in response to an external synchronization signal from the control board of modulator *3* at the moment when the highest value of charging voltage at feeder *4* is reached. The PCSS in chamber *5* is irradiated with a laser pulse with a duration of 5 ns, an optical energy of 25 μJ, and a wavelength of 355 nm with a longitudinally elongated beam profile $\sim 300\,\mu$m in width and 14 mm in length through a PENTA-312 dielectric gel. A filament forms under laser irradiation, which leads to the discharge of charged feeder *4* through high-voltage attenuator *7*.

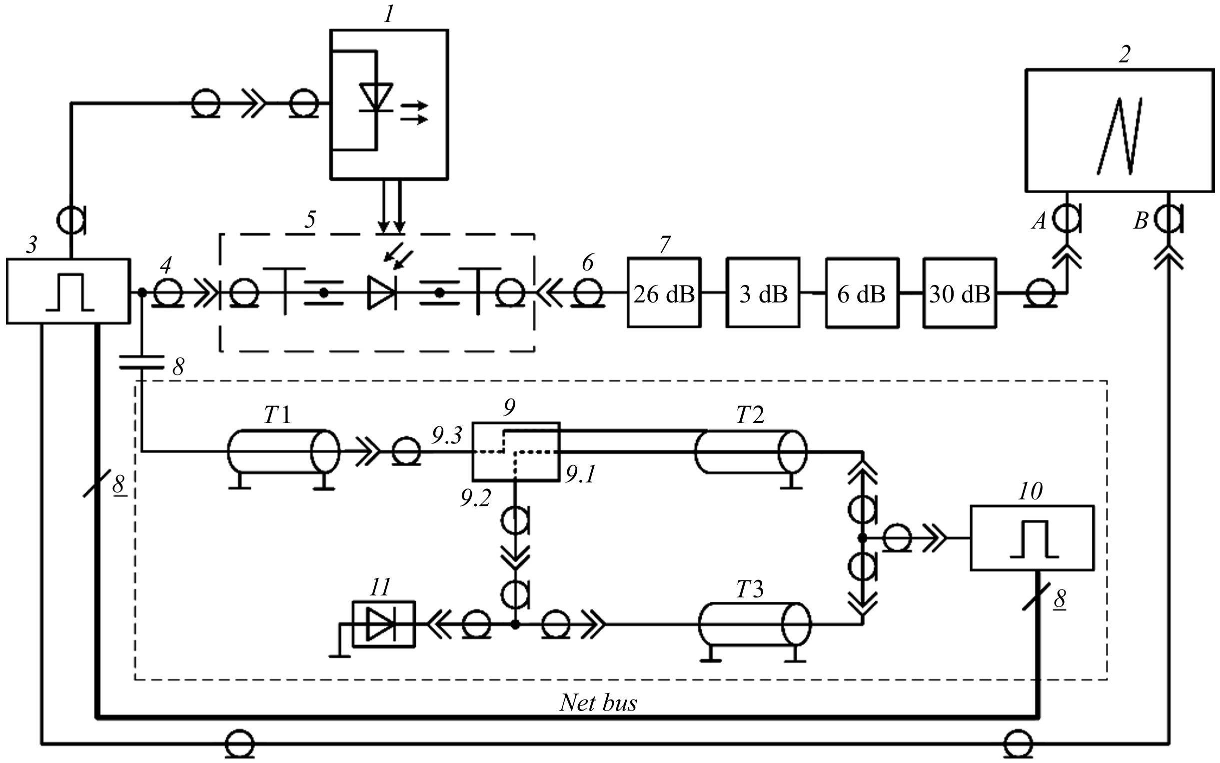

Figure 1. Diagram of the experiment. *1* — DTL-375QT YAG laser, *2* — DSO9254A oscilloscope, *3* — high-voltage source of pulsed charging voltage, *4* and *6* — RFA-7/8 feeder cables, *5* — PCSS waveguide chamber, *7* — AT-20-4 high-voltage attenuator, *8* — KVI-2 high-voltage capacitor, *9* — coaxial T-connector for forming a bipolar signal, *10* — high-voltage rectangular pulse generator, *11* — coaxial waveguide chamber with an S diode, and $T1-T3$ — RK50-2-21 coaxial cables.

At the same time, a test microwave signal is generated at output *9.3* of T-connector *9*. It passes through coaxial cable $T1$ and capacitor *8* ($C = 10$ pF, $U = 10$ kV) and is combined with the charging signal from generator *3* at the input of coaxial cable *4*. Thus, when the PCSS couples feeder *4* to high-voltage attenuator *7*, a coaxial path with a matched load is formed. A test microwave signal propagates along the path in a traveling wave mode through the PCSS with attenuation at the attenuators and detection in channel A of oscilloscope *2* with a bandwidth of 2.5 GHz. The coaxial cable voltage from generator *3* and the original test microwave signal is measured through channel B of oscilloscope *2* with a calibrated high-voltage capacitive divider with a bandwidth of 250 MHz at the junction of the central conductor of coaxial cable *4* and the secondary turn of the high-voltage transformer in generator *3*.

Laser radiation with a wavelength of 355 nm was used in the experiment for its influence through the direct photoelectric effect at a shallow absorption depth of 32.05 nm [6] at $\alpha = 7.1843 \cdot 10^5\,\mathrm{cm}^{-1}$ with a profile that covers completely the interelectrode gap of the PCSS. The test microwave signal frequency of 200 MHz was chosen for its correspondence to the duration of transition of the switch to the conducting state (5 ns). The first stage of the study was coupling the PCSS to a matched load with a test microwave signal (Fig. 2, *a*).

The output pulse front time at the 0.1–0.9 level is $t_f = 4.3$ ns, and the pulse duration at half maximum is $t_d = 46.7$ ns. At the moment of PCSS opening, the charging voltage is $U_c = 11.6$ kV, and the average output pulse amplitude is $U_{out} = -2.96$ kV. The averaged value of the internal PCSS resistance is then $R_i = 47.97\,\Omega$ at current $I_{out} = 59.2$ A, which is a fairly large internal resistance (compared to other experiments). This large resistance, which is comparable to the load, may establish the conditions for enhancement of amplitude of microwave oscillations with a period of 3–4 ns from the front of the output pulse, since this excitation was not detected in [7] in operation with a matched load with $R_i = 39.83\,\Omega$.

Magnification and superimposition of oscilloscope records of the test microwave signal (Fig. 2, *b*) reveal initial amplitude $U_{rf} = 733$ V at amplitude $U_{rf\,out} = 598$ V of the output signal with frequency $f \approx 172.4$ MHz; the internal PCSS impedance is then $Z_i = 11.3\,\Omega$. Passage through the PCSS increases the signal duration by 180 ps. This change is not associated with processes proceeding in the switch, since strong shortening of the period occurs at the moment of reduction of the influencing field and cannot be a condition for sharpening. Such fluctuations of the microwave signal duration are the result of influence of S parameters of the chamber and the measuring instruments (capacitive divider and oscilloscope band).

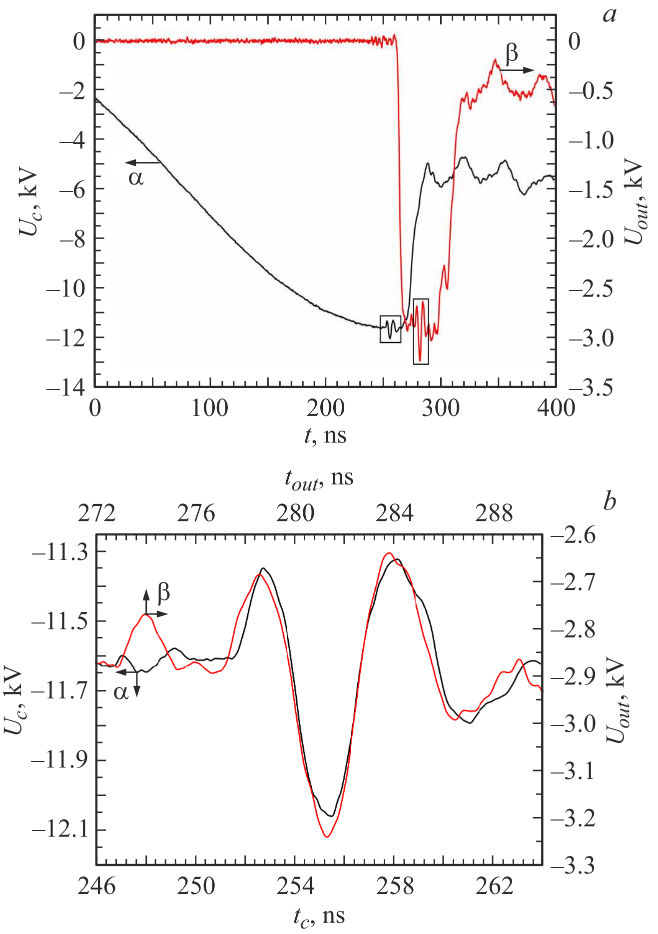

Figure 2. Oscilloscope records in operation with a $50\,\Omega$ load (*a*) and enlarged section of the microwave signal (*b*). α — Oscilloscope record of the charging voltage from the capacitive divider; β — output signal from the attenuator.

The second stage involved replacing the matched load with an extremely small one to establish operating conditions similar to those in a microwave compressor. Thus, a coaxial T-connector with *N*-type connectors with a shorted coaxial load, which produces total resistance $R_{CS} = 42\,\mathrm{m\Omega}$, was installed between high-voltage attenuator *7* and coaxial cable *6* (Fig. 1). The output pulse is differentiated in this case (Fig. 3, *a*) [7]. The charging voltage at the moment of switching is $U_c = 11.6\,\mathrm{kV}$, and the averaged output pulse amplitude is $U_{out} = -21\,\mathrm{V}$; therefore, $I_{out} = 488\,\mathrm{A}$. The specifics of the circuit make it impossible to determine the internal resistance reliably based on the output pulse parameters. The extrema of the output differential signal are $U_{out\,n} = -778\,\mathrm{V}$ and $U_{outp} = 411\,\mathrm{V}$. The temporal characteristics of the output pulse were determined after the output signal was integrated (Fig. 3, *b*): $t_d = 44.7\,\mathrm{ns}$ and $t_f = 5.4\,\mathrm{ns}$.

In the case of operation with a $42\,\mathrm{m\Omega}$ load (Fig. 3, *a*), the test microwave signal amplitude decreases from $U_{rf} = 463\,\mathrm{V}$ to $U_{rf\,out} = 342.5\,\mathrm{V}$ at frequency $f \approx 171.2\,\mathrm{MHz}$; therefore, $Z_i = 14.8\,\mathrm{m\Omega}$. With the signals superimposed (Fig. 3, *c*), one sees an asymmetry of the negative surge and a shift of the zero value of the output microwave signal due to summing of the differential signal and the output microwave signal by voltage from −66 V to 3 V. However, with the output signal shift trend taken into account, the bipolar signal mostly retains its shape, revealing

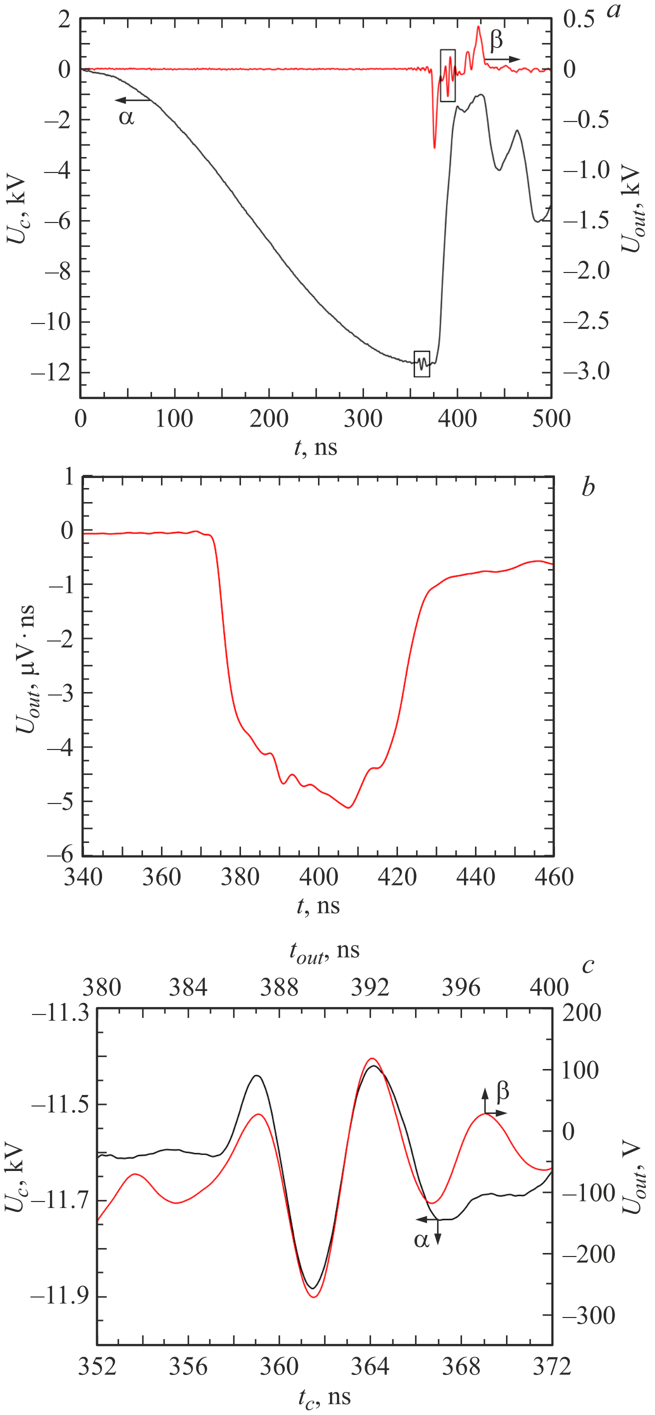

Figure 3. *a* — Oscilloscope records in operation with a $42\,\mathrm{m\Omega}$ load (α — oscilloscope record of the charging voltage from the capacitive divider; β — output signal at the $42\,\mathrm{m\Omega}$ load); *b* — integrated output signal; *c* — enlarged oscilloscope records of the test microwave signal in operation with the $42\,\mathrm{m\Omega}$ load.

potential applicability in the field of high-power microwave signal switching.

The frequency limitation for the acting microwave signal will be determined not by the CFD mechanism, but by the propagation time of a filament until the moment of PCSS closure with the subsequent influence of impedance. It is set by the conditions of propagation of a filament in a semiconductor with a fractal (lightning) structure with conductivity parameters determined by the skin effect at a plasma concentration of $10^{19}\,\mathrm{cm}^{-3}$. When the frequency exceeds 10 GHz, the PCSS will open without a laser due to a delayed avalanche breakdown if the external field is two times stronger than the field of a stationary avalanche breakdown [8].

Thus, the possibility of transmission of a sub-gigahertz microwave signal ($\sim 172\,\mathrm{MHz}$) to a matched load and a $42\,\mathrm{m\Omega}$ load through a PCSS in a nonlinear operating mode under the control of laser radiation was verified experimentally, and the transmission parameters were examined. In matched operation, the duration of the test microwave signal increases by 180 ps under the influence of S parameters of the chamber and measuring instruments, and its amplitude decreases by 18.4 % (or 1.77 dB) due to the PCSS losses. In operation with a shorted load ($42\,\mathrm{m\Omega}$), the output microwave signal features an asymmetric negative surge and a zero value shift due to summing of the differential signal and the output microwave signal by voltage from $-66\,\mathrm{V}$ to 3 V, but its shape is largely retained. Internal resistance $R_i = 47.97\,\Omega$ in the matched mode was achieved in experiments with the PCSS operating based on the CFD mechanism, and the impedance range for the test microwave signal was $Z_i = 11.3\,\Omega$ and $14.8\,\mathrm{m\Omega}$, which corresponds to transmission factors of 1.77 and 2.62 dB for matched and shorted modes, respectively. The main frequency limitation for a microwave signal is not the CFD mechanism itself, but the formation time of a filament and impedance, as well as the magnitude and speed of the applied external field. The relevance of the obtained results lies in the possibility of their wide application in microwave mixers and megawatt-level control circuits of nanosecond microwave devices.

Acknowledgments

The authors wish to thank P.Yu. Chumerin (Tomsk Polytechnic University) and I.A. Prudaev (Tomsk State University) for providing equipment and fruitful discussions.

Funding

This study was carried out under the state assignment (FWRM-2025-0002).

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin