Solid-State Repetitive SOS-based Generator Providing a Peak Power of 4 GW [1]

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Abstract - The paper describes a high-current nanosecond generator providing the peak power of up to 4 GW, the output voltage of 0.4-1 MV, the pulse length of 8-10 ns, and the pulse repetition rate of 300 Hz in the continuous mode and up to 1 kHz in the burst mode of operation. The average output power is up to 30 kW at the pulse repetition rate of 1 kHz. The generator is outfitted with an all-solid-state system of energy switching. The output pulse is formed by a semiconductor opening switch comprising SOS diodes. The electric circuit and the design of the generator have been described. Experimental results have been given. A device for elimination of prepulses across the load has been proposed. Testing results of the device have been reported.

1. Introduction

High-current nanosecond generators equipped with a semiconductor opening switch comprising SOS diodes have been developed recently [1]. SOS generators have an all-solid-state switching system and, therefore, combine a high pulse repetition rate, stability of output parameters, and a long lifetime.

One of major drawbacks of SOS generators is a relatively low peak power as compared to spark-gap generators. The S-5N generator, which is described in [2], represents the most powerful SOS generator providing megavolt pulses at the peak power of 1-1.5 GW and the pulse length of 40-60 ns. However, some applications (specifically high-power relativistic microwave electronics) require shorter and more powerful pulses [3].

The objective of the study was to develop and examine a SOS generator providing the output voltage of 0.4-1 MV, the pulse length of less than 10 ns, and the peak power higher than 3 GW.

2. Circuitry and design of the generator

The electric circuit diagram of the generator is shown in Fig. 1. The item 1 means elements of the output unit of the S-5N generator [2], which was used as the base unit. The generator output was connected to an additional energy compression unit (2, 3) including the pumping capacitor C2, the magnetic switch MS^-, the inductive storage L2 and the semiconductor opening switch SOS2.

The circuitry operates as follows. As soon as the switch SOS1 cuts off the reverse current, the energy stored in the inductive elements of the circuit 1 is supplied to the unit 2 as a positive-polarity pulse. The energy is transferred to the capacitor C2 and the current passes via the switch SOS2 ensuring its forward pumping. The core of the magnetic switch MS^- is saturated by the moment the maximum voltage is built up across the capacitor C2 (the end of the forward pumping current pulse). The capacitor C2 discharges via SOS2 in the reverse direction and the energy is transferred to the inductance of the elements in the reverse pumping circuit. When the switch SOS2 cuts off the reverse current, the energy passes via the transmission line 4 to the generator load R and forms a short negative-polarity pulse across this load.

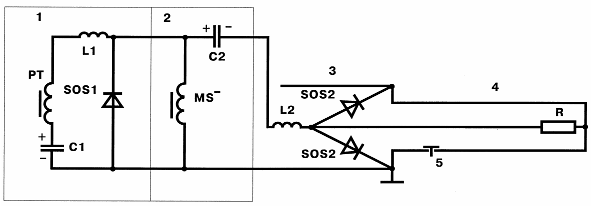

Fig.1. Circuit of the generator: 1 - elements of the output unit of the S-5N generator [2]; 2 and 3 - final energy compression and peak power amplifying units; 4 - transmission line; 5 - capacitive voltage divider.

The final power amplifying units 2 and 3 were designed as an individual module, which was connected to the output of the base generator 1. The elements C2 and MS^- were installed in the oil-filled tank 2 measuring $1.1 \times 1.0 \times 0.6$ m^3. The outlet end face of the tank received the cylindrical section 3 with diameter of 480 mm and length of 600 mm, which housed the elements L2 and SOS2. The transmission line 4, which was

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terminated to the matched load R, was connected to the section 3. All the sections, including the tank of the base generator, formed a single oil volume.

The pumping capacitor bank C2 contained 400 ceramic capacitors and was rated at 250 pF at the working voltage of up to 600 kV. The single-turn magnetic switch MS^- was made up of the central electrode (metal tube of 90 mm in diameter) and 41 ferrite ring cores having 180-mm outer diameter. The core magnetization was reversed using an external DC source (not shown in Fig. 1) rated at 15 A, which was connected to the high-voltage terminal of the switch (the connection point of C2 and MS^-). LC-filter (L ~ 0.26 mH and C ~ 70 mF) protected the current source from pulsed voltage.

The opening switch SOS2 was rated at the working voltage of 1 MV. It contained eight SOS diodes: two parallel branches of four series-connected SOS diodes each. The SOS diode had the following parameters: the reverse voltage of up to 270 kV at the pulse length of about 10 ns; the number of series-connected semiconductor structures equal to 240 with the structure surface area of 2 cm^2. The SOS diodes were connected in a zigzag pattern to make the opening switch shorter. The SOS2 switch is about 450 mm long.

Load characteristics of the generator in the burst mode of operation were measured using the transmission line 4, which was terminated to the matching load R made up of parallel-series connected carbon resistors. The line was 1400 mm long and 275 mm in outer diameter. The load was installed on the length of 450 mm at the end of the line.

The line was outfitted with three removable internal electrodes 80, 25 and 8 mm in diameter for adjusting its wave impedance equal to 50, 100 and 150 Ω respectively. If the load had a higher resistance, the line was disconnected and the load resistors were placed on the axis of the section 3 between two branches of the opening switch SOS2.

When the generator was tested in the continuous mode of operation, a water load with circulation and forced cooling of the working liquid was installed in the section 3.

Measurement means included current shunts in both branches of SOS2 and the load R, and capacitive voltage dividers installed in the section 3 and the transmission line 4. The intrinsic rise time of the signal in the shunts did not exceed 0.5 ns. Pulses were recorded using a TDS684 oscilloscope with 1-GHz bandwidth and wideband signal attenuators (Barth Electronics Inc).

3. Test results

Preliminary experiments were aimed at optimization of the value of the capacitance C2. All other things being equal, it determines, on the one hand, the energy transferred from the base unit to the power amplifying unit and, on the other hand, pumping parameters of the opening switch SOS2. A nearly optimal value of the capacitor C2 was ~250 pF. If the capacitor value was smaller, the energy transferred to the capacitor C2 decreased. If the capacitor value was larger, the forward and reverse pumping time of SOS2 increased and, therefore, the output pulse less than 10 ns long could not be generated.

The value of the inductive storage L2 was optimized too. Over the interval of the external load R from 50 to 300 Ω, the largest peak power across the load was obtained at L2 ~ 1 μH.

The following results were obtained. The time for the energy transfer from the base unit to the capacitor C2, which was equal to the forward pumping time of SOS2, was ~60 ns. The current had the amplitude of 3.9 kA. The energy stored in C2 was about 42 J at the voltage of ~580 kV. When the switch MS^- was saturated and the capacitor C2 discharged, the reverse current through the SOS2 increased up to ~7 kA during ~30 ns and then was cut off by the opening switch in a time of less than 3 ns.

Fig. 2 presents typical waveforms of the reverse current in one branch of the SOS2 and the voltage across the load R. The shapes and the amplitudes of the currents in two parallel branches of SOS2 differed by not more than 3%, which was within the measurement accuracy. At R = 50-300 Ω the current cutoff time, which was measured at 0.1-0.9 of the amplitude value, was within 2-3 ns, the load current rise time was 4 to 4.5 ns, and the pulse length (FWHM) was 8 to 10 ns.

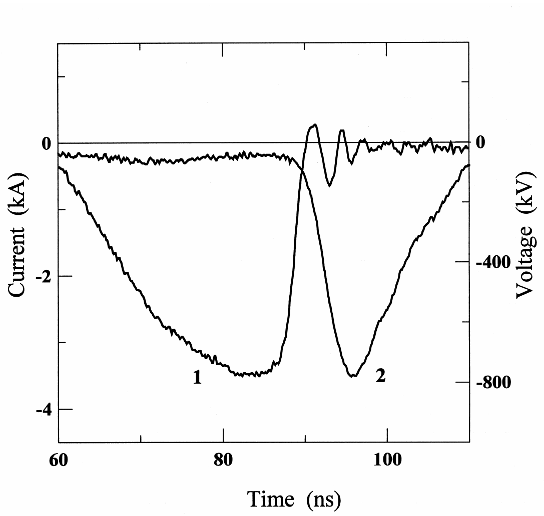

Fig.2. Typical waveforms of the reverse current in one branch of the SOS2 (1) and the voltage across the load R (2).

The Table. I shows output characteristics of the generator: ρ - wave impedance of the matched transmission line, R - external load resistance without using the line, U - output voltage amplitude in the line or across the load, W - pulse energy, P - peak power of the pulse, and I^- - amplitude of the current cut off by the SOS2.

The amplitude I^- weakly increased with growing external load of the generator due to the decreasing the current branched to the load during the SOS2 pumping. The maximum peak power equal to 4 GW was obtained in the line with ρ = 150 Ohm.

Table I. Output parameters of the generator

ρ (R), Ω	U, kV	W, J	P, GW	I^-, kA
ρ = 50	390	19	3.0	6.1
ρ = 100	570	25	3.2	6.5
ρ = 150	780	30	4.0	7.0
R = 270	950	23	3.3	7.2

The thermal tests in the continuous mode of operation were performed using a section of a glassy-epoxy tube 100-mm in internal diameter and 410 mm long as the generator load. The tube had two end-face metal electrodes of 50 mm in diameter. The distance between electrodes was 380 mm. On the side of the grounded electrode the tube was connected to a cooled tank having the holding capacity of 0.3 m^3, which was filled with an aqueous solution of NaCl. The solution was pumped through the tube at a rate of ~10 l/min in a closed loop. The test load resistance was 140 to 148 Ω, at which the generator output voltage was 700-750 kV and the peak power was 3.5-3.8 GW. The pulse length was ~10 ns and the pulse energy was ~28-30 J.

The oil circulation and cooling system of the base unit was used for oil cooling in the power amplifying units since all units had a single oil volume. The pulse repetition rate F and the operating time depended on the frequency capability of the base generator. The tests were performed under the following regimes: continuous operation at F = 300 Hz for 1 hour and burst operation at F = 500 Hz for 3 minutes followed by a 5-min rest period (10 bursts) and F = 1 kHz for 1 minute followed by a 5-min rest period (10 bursts). The elements were not overheated and output characteristics were not changed in all tested regimes.

4. Prepulse suppressor

It was demonstrated [4] that prepulses, which appear during forward and reverse pumping of the semiconductor opening switch, have an adverse effect on the field-emission graphite cathode used in the electron diode of relativistic microwave generators. In this connection, the other part of the study dealt with the possibility of eliminating prepulses across the load.

Amplitudes of the positive and negative prepulses weakly depended on the external load resistance and were equal to about 40 and 65 kV respectively. The diagram in Fig. 3 shows a circuit having a prepulse suppressor (PPS). PPS was connected in series with the external load R and contained two back-to-back semiconductor diodes.

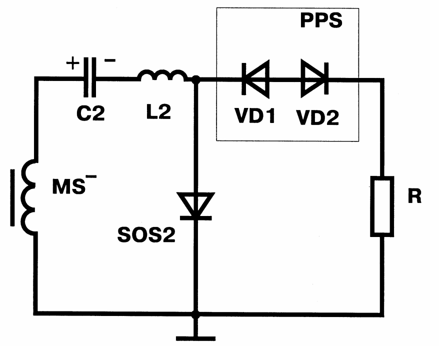

Fig.3. Circuit of the prepulse suppressor (PPS).

The operating principle of the suppressor is as follows. When a forward current passes via SOS2, the diode VD1 is open and blocks the positive prepulse across the load. During reverse pumping the diode VD1 passes the current but the diode VD2 is open and blocks the negative prepulse. When the opening switch SOS2 cuts off the current, the opening switch voltage rises up at a rate of about 150 kV/ns, leading to excitation of an ionization shock wave in the reverse-biased diode VD2. Electron-hole plasma fills the diode VD2 in less than 1 ns and the diode switches the voltage pulse to the load.

PPS optimization consisted in selection of the number of series-connected structures and their surface area in the diodes VD1 and VD2 observing two criteria, namely minimum amplitude of prepulses across the load and a minimum loss of power in PPS at conduction stage. The same semiconductor structures as those in SOS2 were used in the experiments. The best results were obtained taking the following parameters of the diodes: the number of series-connected structures equal to 160 and 80 and their surface area equal to 2 and 4 cm^2 for VD1 and VD2 respectively (two parallel columns having the surface area of 2 cm^2 each were used in VD2).

Figs. 4a and 4b present waveforms of a voltage pulse in the line having ρ = 150 Ω without and with PPS. The positive prepulse was eliminated completely, while the amplitude of the negative prepulse was about 16 kV (~2% of the main pulse amplitude). When PPS was used, the pulse amplitude in the line was 750 kV, the peak power was 3.7 GW, and the pulse length was 10 ns. If the number of series-connected structures in VD2 was increased further, the negative prepulse was eliminated completely either, but the amplitude and the peak power of the main pulse decreased significantly (~700 kV and 3.2 GW when VD2 contained 120 series-connected structures).

A photograph of the PPS is given in Fig. 5. The device is 160 mm long. The switched current is 4 kA. PPS was fitted on the axis of the section 3 (Fig. 1) between the opening switch branches ahead of the entry to the transmission line 4.

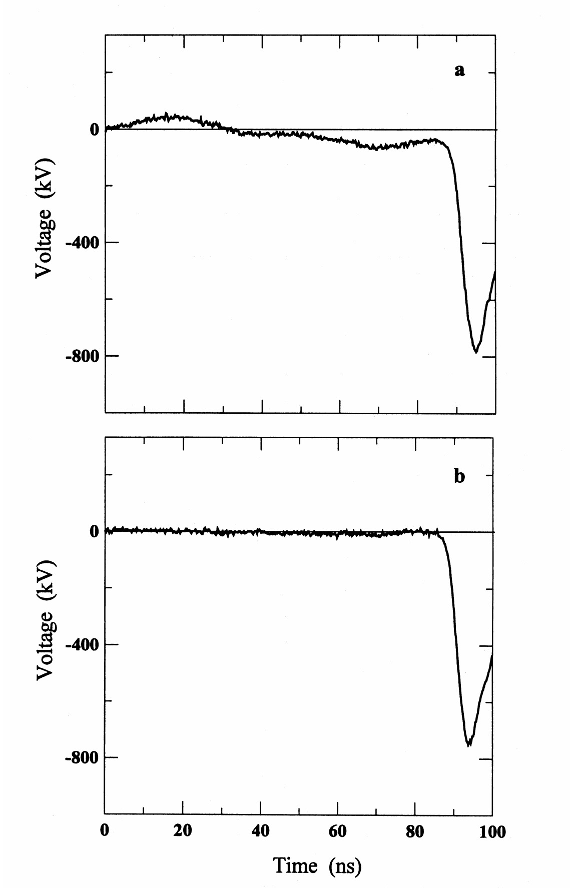

Fig.4. Waveforms of a voltage pulse in the line at ρ = 150 Ω without PPS (a) and with PPS (b).

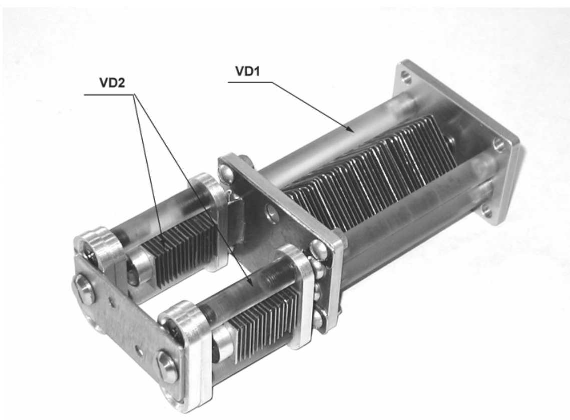

Fig.5. External appearance of the prepulse suppressor.

PPS was tested in the burst mode at pulse repetition frequency F = 1 kHz. The burst length was 2 seconds followed by a 1-min rest period. The testing regime was determined by a limited dissipating power of the matching resistors R in the line. Several test runs were performed. Twenty bursts were produced in each test run. No changes were observed in the PPS working characteristics (appearance of prepulses, diminishing of the pulse amplitude in the line or changes of the pulse shape).

5. Conclusion

This study demonstrated that it is possible to design SOS generators with the peak power of up to 4 GW, the pulse length of 8-10 ns, the pulse repetition rate of 1 kHz, and the average output power of up to 30 kW. The solid-state switching system, which included magnetic switches and semiconductor devices, ensured a highly stable shape of generated pulses.

The newly designed prepulse suppressor allows using the generator for supply of electron diodes in high-powerful relativistic microwave generators.

If the matter concerns further shortening of the pulse and the increase of its peak power, which is necessary in particular for development of pulse generators intended to supply powerful ultrawideband irradiators, we can comment as follows. The rise time of the voltage pulse at the generator output, which was equal to about 4 ns, is sufficient for engagement of the next step of power peaking with semiconductor sharpener based on a DBD switch (delayed breakdown diode). The scheme may be similar to the one used in [5] when a DBD switch having a large number of series-connected semiconductor structures operated in the wave switching regime and provided shortening of the input pulse and increasing its peak power.

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