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Experimental Research of the Explosive Plasma Antenna

Contents

Abstract

The multirod plasma antenna based on HE-shaped plasma jets experimentally investigated. The developed plasma antenna with four rods is shown to exhibit more than $6 \div 7$ dB gain at the frequency of 700 MHz.

1. Introduction

During last several years the heightened interest exists to the feasibility of plasma antennas (PA) development. Such antennas use plasma formations as the receiver or transmitter elements. The characteristics of the plasma formations are determined by purpose of the specific antenna. Development of such devices is stimulated by their following basic potential capabilities:

- rapid change of antennas and antenna arrays configuration. Controlling their beam pattern and its orientation by electronic control of plasma parameters;
- small effective radar cross-section (RCS) of such antennas in a wide frequency band;
- effective suppression of multipath reflection while transmitting short high-power signals;
- high level of electromagnetic compatibility of the devices, equipped by PA that allows using their large number at the small area;
- design of the compact extendable antennas for use with the high-power pulse generators.

Enumerated potential PA capabilities boosted intensive research and several design programs, targeted on the development of PA systems for various applications.

The majority of recent PA studies, were performed with PA, based on the pulse or steady-state discharges in various gases at low pressures [1,2]. Obtained results have shown a potential opportunity of manufacturing PA, using gas discharges in the dielectric tubes. Though the parameters of such antennas currently are somewhat worse, than those of the metal antennas, nevertheless, intensive efforts in this direction are continued.

The special place among PA studies is occupied by studies, whose objective is manufacturing extendable antennas for high-power pulsed compact generators. In this case, use of gas discharges in the dielectric tubes is not an option, due to design and operational issues.

One of the most prospective, though also complicated path to the solution of the specified problem, is the design of lengthy plasma jets using high explosives (HE) [3,4].

HE-shaped plasma jets can be used for designing PA if they have appropriate electrophysical and geometrical properties and maintain an electrical contact with an explosive jets source for a period of time, exceeding radiation pulse length of the generator.

In view of complexity of the processes accompanying forming and propagation of such jets in the air, their theoretical study or computer simulation is practically impossible. Therefore, despite major expenses of time and resources, the

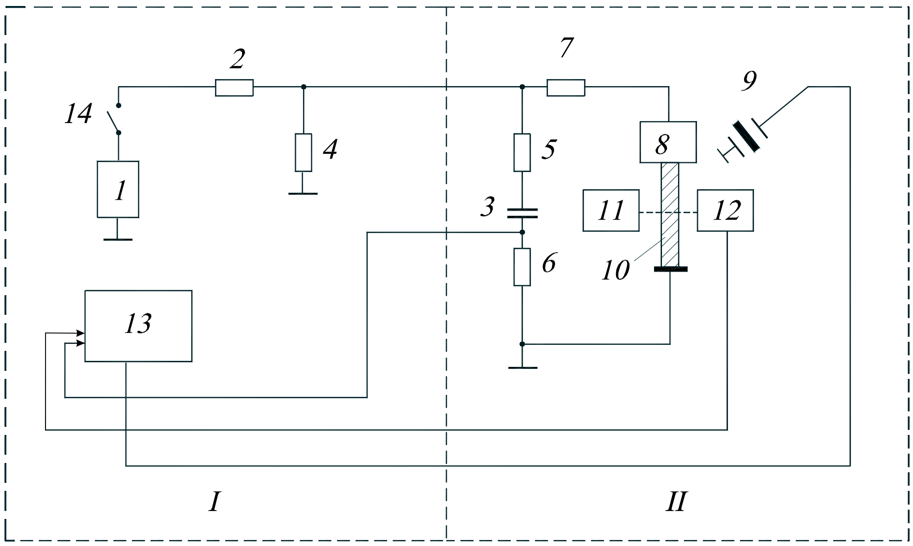

Fig. 1. The block diagram of the experimental stand for studying electrophysical properties of HE-shaped plasma jets. 1 constant-voltage source; 2 limiting resistor; 3 capacitive storage; 4 digital multimeter; 5 internal resistance of the capacitor storage; 6 the shunt for the discharge current measurement; 7 resistance of a plasma jet; 8 HE cartridge, generating a plasma jet; 9 piezoelectric transducer; 10 plasma jet; 11 laser; 12 photodetector; 13 digital storage oscilloscope; 14 switch.

most realistic approach is the experimental research of geometry and conductance of the HE-shaped plasma jets.

2. Experimental Research of Electrophysical Properties of the HE-shaped Plasma Jets

One of the most important parameters determining feasibility to use HE-shaped jets in plasma antennas is their conductance.

Studies of HE-shaped plasma jets conductance are performed for a long time in connection with MHD generators development [5], and cumulative jets control using strong pulsed magnetic fields [6–8]. Plasma streams with the lengths up to 40 cm with a specific conductivity $10^3 \div 10^4$ (Ohm·m)$^{-1}$ have been obtained [6–8].

However, these results were obtained for rather long pulses ($10^{-1} \div 10^{-3}$ s), relevant for the specific problems.

In our case, since HE-shaped jets are intended for use in PA for the high-power short pulses generators working over the frequency range $0.5 \div 1.2$ GHz, previously obtained jets performance appears unsuitable.

In this connection, we investigated feasibility of plasma jets shaping by HE cartridges, capable for building PA for the generators with short $\sim 10^{-8} \div 10^{-7}$ s pulse length.

Block diagram of the experimental installation for studying electrophysical performances of the plasma jets, shaped with HE, is presented at the Fig. 1.

The stand contains salvageable part I and expendable part II. Capacitor storage (3) is charged by the constant-voltage source (1) adjusted from 10 up to 300 V and verified by a digital multimeter. Power supply is connected through the circuit switch (14), and the charge current is limited by the resistor (2). The oscilloscope (13) is triggered by signal from the piezoelectric transducer (9). The plasma jet (10) is shaped by a cartridge (8). Interruption of an optical line-of-sight between the laser (11) and a photodetector (12) is recorded by the oscilloscope (13) and witnesses jet appearance in the gap between cartridge and the second discharge electrode of the capacitor storage (3) (target). The discharge current is recorded by the oscilloscope (13) by using shunt resistor (6).

Expendable part of the experimental stand, set on a test platform, is shown at the Fig. 2.

We used the electrocontact method [6,9] for measurement of the electrophysical characteristics of the plasma jets. We have chosen this method due its simple implementation and reliability by operation in the field range conditions. It is important, that it also allows to monitor maintenance of an electrical contact between plasma jet and a cartridge forming it. This condition is extremely important for the designing specific the plasma antenna.

Equivalent circuit, illustrating used measurement procedure, is given at the Fig. 3.

Storage 5700 ± 10 μF (3) is charged by the

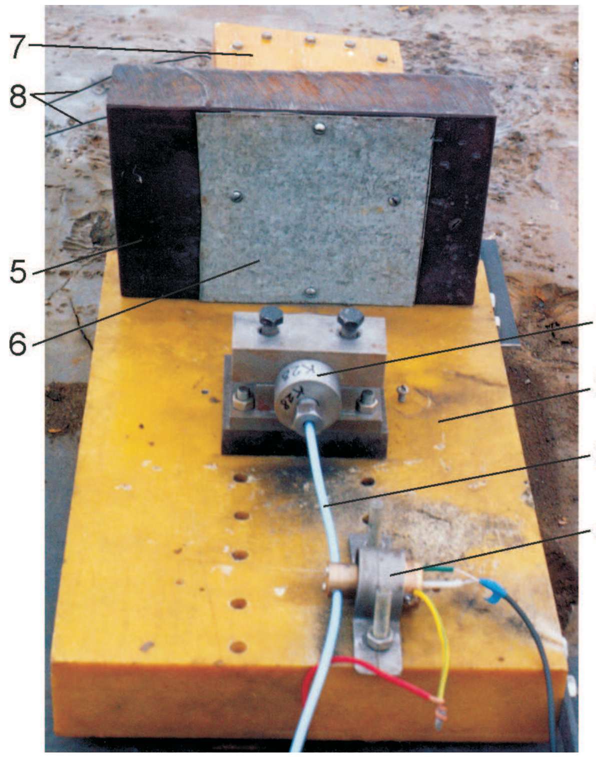

Fig. 2. Expendable part of the experimental stand: 1 HE cartridge, generating plasma jet; 2 dielectric plate; 3 detonation cord; 4 piezoelectric transducer; 5 massive steel plate acting like a target; 6 galvanized iron plate; 7 capacitive storage; 8 cables.

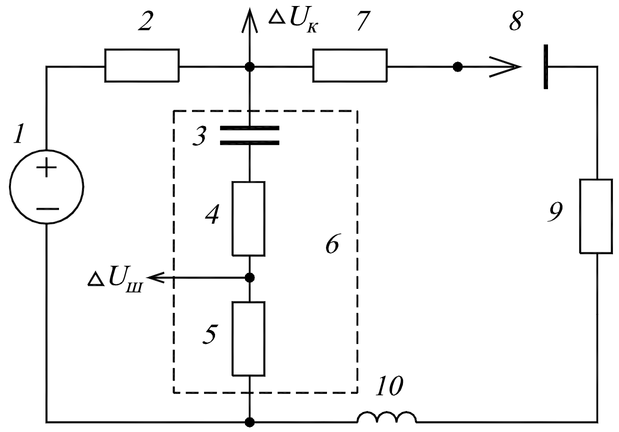

Fig. 3. Equivalent circuit, demonstrating conductivity measurement by the electrocontact technique: 1 power supply; 2 charger resistor; 3 the equivalent capacity of the energy storage; 4 internal capacitive reactance of the store; 5 resistance of the measurement shunt; 6 storage capacitor; 7 equivalent resistance of the connecting circuit elements; 8 section "explosive cartridge — jet absorber"; 9 jet resistance; 10 equivalent inductance of the stand.

independent power supply (1), voltage adjustable $10 \div 300$ V, through the charging resistor 3.8 kOhm (2) The charge current passes through the shunt (5) with resistance 0.064 ± 0.001 Ohm. Storage (3) is built from three 1500 uF paralleled capacitors. Entire impedance of all electrical connections in the stand does not exceed 10^{-2} Ohm.

The equivalent inductor (10) accounts for inductance of the capacitor storage, interconnects and plasma jet inductance. Change of its value was performed after preliminary experiments on the jet geometrical sizes measurement. The inductance can be calculated using equation:

$$L_c = \frac{\mu_0}{4\pi}\left(\ln\left(\frac{2l}{r_c} - 1\right)\right) \cdot l,$$

where μ_0 is permeability, $\mu_0 = 4\pi \cdot 10^{-7}$ Hn/m, l is distance between a flange of a cartridge and a plate (ranging from 5.6 cm to 24.5 cm), r_c is radius of a jet. For $r_c = 0.5$ cm, $l = 14.5$ cm value of inductance is estimated $L_c \simeq 0.6$ μH.

Before the field tests, the stand was tested in laboratory by using semiconductor simulator of plasma jet resistance. Operation of the equivalent circuitry was simulated using specialized software.

We have obtained satisfactory conformity when comparing results of laboratory experiments with the jet simulator and its computer model. Comparison was carried out for the equivalent inductance (10) equal to 0.22 μH, an internal resistance (4) equal to $7 \cdot 10^{-3}$ Ohm and entire impedance of interconnect circuitry (10) to equal 10^{-2} Ohm. Modeling has shown, that the used stand allows to measure jet resistance starting from $\sim 10^{-2}$ Ohm up to tens of Ohms.

Typical current risetime in a discharge circuit of the used capacitor storage did not exceed 5 μs.

Plasma jets intended for use in the plasma antenna were shaped using special cartridges equipped with various HE compositions, including certain impurities. We have tested several cartridge designs during the tests. Initial cartridge designs based on the special shaping nozzles, appeared inapplicable for certain types of HE. Their basic shortcoming was nozzle fracturing, causing failure of an electrical contact between jet and a cartridge. Therefore, we have tested other cartridge designs. The following goals for the cartridges were set:

- maintenance of a reliable electrical contact between plasma jet and cartridge;
- maximizing jet conductance ;
- maximizing highly-conductive jet length while keeping jet diameter $\sim 10 \div 12$ mm;
- reduction of HE charge, which shapes a plasma jet.

To design cartridge, as much as possible satisfying simultaneously all listed requirements, we had to

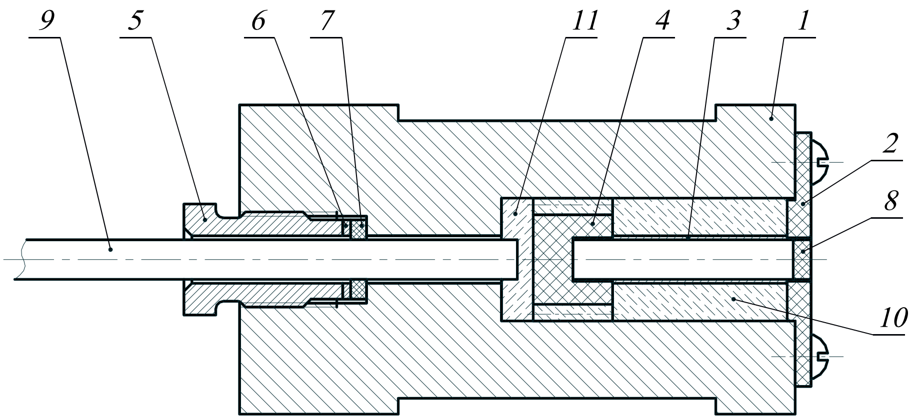

Fig. 4. Design of the cartridge with a cylindrical charge and a copper tube: 1 housing; 2 washer; 3 tube; 4 perforator; 5 spigot; 6 washer; 7 spacer; 8 fuse; 9 detonation cord; 10 sizing compound 1; 11 sizing compound 2.

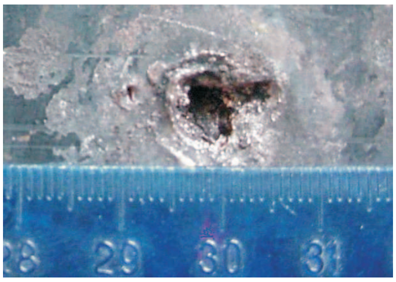

Fig. 5. Imprint of a plasma jet on a metal target. Distance from a cartridge to the target is 145 mm.

resort to the comparison of the experimental results obtained for cartridges of various designs, filled by different HE types with impurities or without them. Having conducted significant number of tests and the analysis of their results, we have chosen cylindrical cartridge design with a copper tube. Its design is shown at the Fig. 4.

Loaded HE cartridges were mounted on the experimental stand. Their demolition was performed using a detonation cord. Diameter of a plasma jet was determined by its imprint on the zinc-plated metal sheet, mounted on a thick metal plate at the given distance from the cartridge. Use of a zinc-plated a target allowed to record imprints of the jet, shaped by using copper inserts of the various shape (conical, spherical, cylindrical). In separate series of experiments copper plates were used in the capacity of targets. The reference imprint of a plasma jet is shown at the Fig. 5.

At the Fig. 5, one can clearly see tracks of gas and metal (conductive) jets at the metal target, as well as the tracks left by the detonation products. Melted edges of a crater, and deposited copper, witness high temperature in a region of a plasma jet and a plate interaction.

Performed analysis of various imprints shown, that at the distance of $\sim$ 145 mm from cartridge exit section, diameter of a plasma jet varies from experiment to experiment within $7 \div 12$ mm. Such changes are caused by used composition and geometry of HE charge.

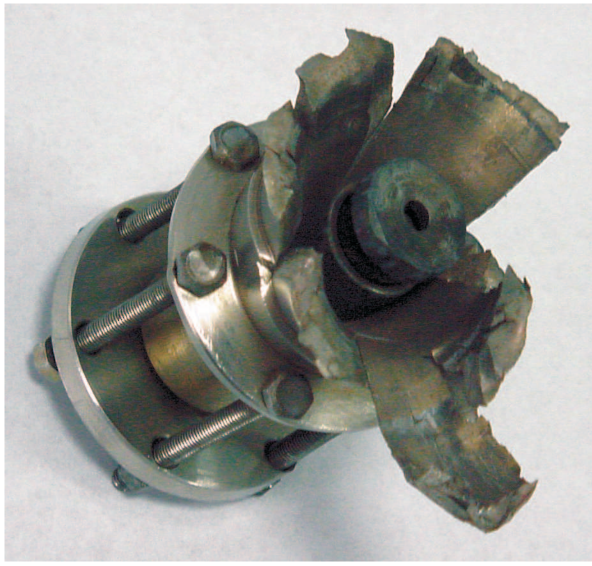

Fig. 6. Cartridge photograph after explosion.

At the larger distances between cartridge and a target up to 245 mm the jet diameter, accordingly, was larger too.

Performed analysis of the obtained repeatable results, has shown that the size of a high-temperature conductive part of the jet are, apparently, much less, than the size of an imprint on a metal target. However, it was not possible to size the imprint on the metal target more accurately.

Fig. 6 shows the photograph of a cartridge after explosion.

Visualization of shaped jets diameter is only one of the important properties of the plasma jet used in PA. To measure other important property, conductance of a jet, its length and time duration of contact

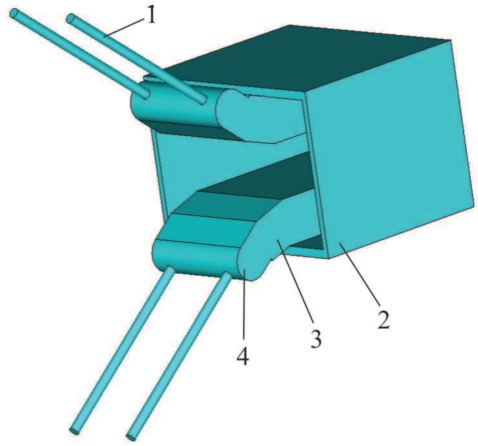

Fig. 7. Sketch of the multirod plasma antenna: 1 HE-cartridge shaped plasma jets; 2 H-waveguide; 3 edges of H-waveguide; 4 explosive cartridges assembly.

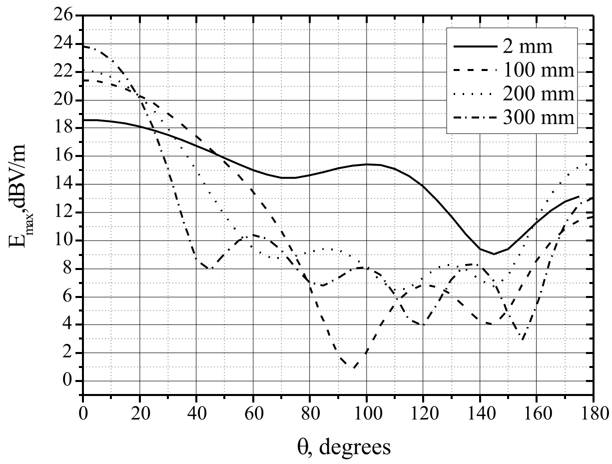

Fig. 8. E-field strength of the four-jet antenna in E-plane for various lengths of a conductive plasma jet. Frequency of radiation is 700 MHz.

Fig. 9. General view of the four-jet plasma antenna prototype with the H-waveguide exciter.

maintenance between jet and a cartridge, we recorded waveforms of voltage pulses and a capacitor storage discharge current flowing through a plasma jet. The oscilloscope was triggered by a voltage pulse from the piezoelectric transducer, mounted at the detonation cord.

Jet velocity was computed from a known distance between a cartridge and a target and transit time of a plasma jet. This time was measured as a delta between the moment of a jet exit from a nozzle and the jet contact with a target.

The moment of a jet exit was determined by absorption of laser beam, positioned 2 mm apart from the cartridge nozzle. The moment of contact with the target was determined by start of a current flow between a cartridge and a target through a jet. Time of the electrical contact existence between jet and cartridge was determined by the length of a discharge current pulse.

The length of a jet is determined by the expression:

$$l_j = l_0 + V_j \cdot t$$

where: l_0 base distance in centimeters between cartridge nozzle and a plate; V_j jet velocity; t is a contact duration.

Postprocessing of the numerous explosive experiments with cartridges of the various designs, charged with HE with various impurities, allowed to obtain plasma jets conductance $6 \cdot 10^2 \div 7 \cdot 10^3$ $(\text{Ohm}{\cdot}\text{m})^{-1}$.

The obtained results are close to those, present in publication [6–8]. The considerable conductance scatter is apparently caused by two reasons: instability of jet — target section resistance and use of granulated HE.

The length of plasma jets with this conductance, maintaining an electrical contact with a cartridge, achieved in the experiments was equal to $21 \div 22$ cm.

Performed estimates showed that the HE-shaped plasma jets generated by HE have all the properties, allowing using them for certain modifications of PA.

3. An Experimental Research of the Multirod Plasma Antenna

Undertaken theoretical analysis and computer modeling several plasma antenna types, shaped

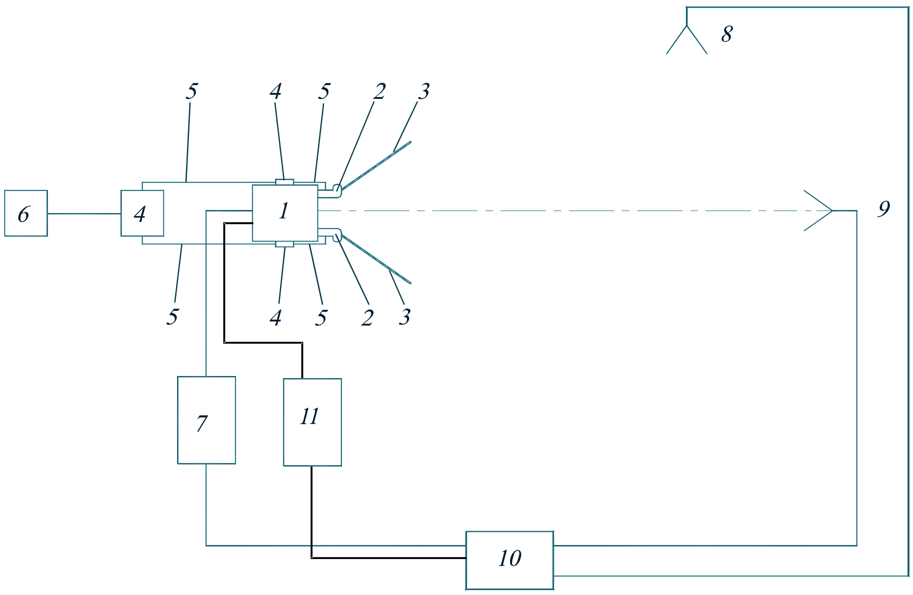

Fig. 10. Block chart of the explosive plasma antenna experiment: 1 H-waveguide antenna exciter; 2 the explosive cartridges, which shape plasma jets; 3 conductive plasma jets; 4 detonation distribution units; 5 detonation cords; 6 primary detonator; 7 700 MHz RF emission generator; 8 the antenna recording radiation in 40^0 to the line-of-sight; 9 line-of-sight radiation recording antenna; 10 a four-channel digital storage oscilloscope with 1.5 GHz bandwidth; 11 a piezoelectric transducer.

by HE, has shown that in our case the most realistic approach is design of the multirod plasma antenna. This choice is conditioned by our plasma antenna excitation system, based on the H-waveguide. The design of multirod PA with the H-waveguide excitation system is shown at the Fig. 7.

It is clear from the figure, that such an antenna is actually a variety of the well-known multipole antennas widely used for radiation of powerful UWB-pulses. Its only is that instead of conventional metal rods, in our case we use the conductive plasma jets, shaped by HE charges.

To verify operation of such an antenna with plasma jets, whose parameters we addressed in the previous section, we performed computer modeling of the antenna. At the first stage, the operation of antenna, using six plasma jets, was simulated. However, recognizing that for the purpose of device survivability it is necessary to reduce HE quantity, we have also modeled operation of the antenna with four plasma jets Fig. 7. Comparison of the simulation results for the antenna, operating at the frequency of 700 MHz, with four and six HE-shaped jets, shown that the basic characteristics of both antennas are virtually same. Therefore, to reduce the total weight of HE we picked a four-beam design. Computer simulation results) are presented at the Fig. 8.

Analyzing the results of computer simulation, shown at the Fig. 8, it is possible to see, that at the frequencies of 700 MHz the influence of plasma jets is substantial enough for their length of 200 mm.

Taking into account computer simulation results we have developed and experimentally studied laboratory prototype of PA with H-waveguide exciter. The plasma jets were substituted by the metal pipe sections. Prototype photo is shown at the Fig. 9.

The laboratory experimental tests have shown good agreement with the results of computer modeling, shown at the Fig. 8.

Having conducted PA prototype study and verified reliability of instrumentation system in laboratory condition, we carried out explosive experiments on the antenna operation. The experiments were performed at the experimental stand with the block diagram, shown at the Fig. 10.

The PA at this stand was excited by the H-waveguide (1). Two supports (2) are mounted at the exit of the waveguide. The set of 2 explosive cartridges (3), shaping plasma jet, are installed in each support. Synchronous detonation of all cartridges was performed using a set of detonation cords (5) through the detonation distribution unit (4) from the initial detonator (6). The H-waveguide exciter (1) was fed by the RF oscillator (7) with 2W output and 700 MHz frequency. The generator is self-contained unit and could work in pulsied or CW regime. If needed, operation frequency and output power of the generator (7) can be remotely (15 meters) tuned from 600 MHz to 800 MHz. The emitted signal was received by two broadband antennas (8) and (9) positioned in such a way that one antenna (9), received the transmitted signal at the PA line-of-sight, while another one (8) is at 40^0 to the line-of-sight. Signals from antennas (8) and (9) and signal from the

Fig. 11. Photograph of a plasma antenna H-waveguide exciter with HE cartridges installation platforms.

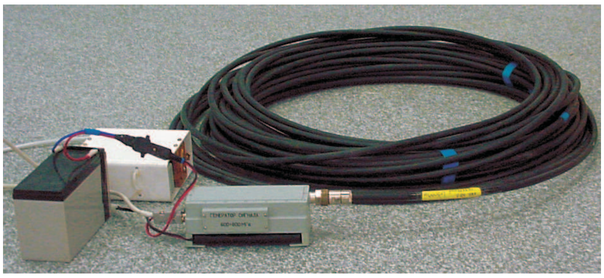

Fig. 12. Picture of the RF generator with remote-control unit, batteries and connector cables.

generator (7) was recorded by the broadband digital storage oscilloscope. The oscilloscope was triggered by a signal from the piezoelectric transducer, mounted on the detonation cord.

Photograph of the H-waveguide PA exciter with two platforms for explosive cartridges installation is shown at the Fig. 11.

Fig. 13. shows photographs of two receiver broadband, designed for PA emission registration over the frequency range 600 ÷ 800 MHz.

The overall performance of the plasma antenna was tested as follows (see Fig. 10). Before detonating cartridges (2) the RF generator (7) was turned on and the oscilloscope (10) recorded the signal level, at the output of each antennas (8) and (9). After detonating cartridges (2) the received signal level at the antennas output was recorded again. Redistribution of the received signals amplitudes (rise of the signal received by the line-of-sight antenna (9) and reduction of a signal level, received by the antenna (8), in comparison with the signal levels, received by each antenna before cartridge detonation, proved PA operation.

Before detonating the HE cartridges, the signal received by line-of-sight antenna (9), on exceeded a signal received by the antenna (8) by 10 %.

After detonation of cartridges and formation of four-beam PA, the signal recorded by the line-of-sight antenna (9), increased by 30 % in comparison with a signal recorded before detonation. Simultaneously, the

Fig. 13. The broadband antennas for recording RF emission of the plasma antenna.

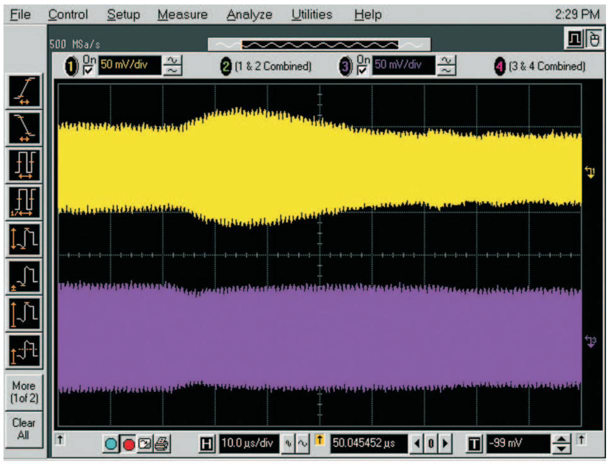

Fig. 14. Waveform, illustrating signal ratio between the receiver antennas before detonation and after detonation of PA. Top channel is a signal from the line-of-sight antenna. Bottom channel is a signal from the antenna, positioned at 40^0 to the line-of-sight.

signal received by the antenna (8), decreased by 10 % in comparison with that before detonation.

One of the oscillograms, illustrating this redistribution, is shown at the Fig. 14. Top waveform of the oscilloscope represents signal, received from the line-of-sight antenna (9), while the bottom waveform, represents the signal, received by the antenna (8), which is at 40^0 angle to the line-of-sight.

The waveforms clearly show that after the detonation of PA, the line-of-sight antenna output signal rises, while the signal, received from the output of the antenna, at 40^0 to the line-of-sight falls. This redistribution is observed only for the time of the plasma antenna existence. Higher level of the signal, received from the antenna, at 40^0 angle to the line of sight is predetermined by the calibration of experiment.

The RF generator photo with a remote control unit, batteries and connecting cable is shown at the Fig. 12.

Such redistribution of signal energy, repeatable observed during the experiments, proves the functioning of the multirod explosive plasma antenna. Processing and analysis of the results proved that achieved PA gain exceeds $6 \div 7$ dB.

4. Conclusion

Experimental study results presented for the multirod plasma antenna, shaped by HE charges, in the emissive mode.

Electrophysical and geometrical characteristics of the plasma jets shaped with help HE of a various composition are investigated.

It has been shown that using a special composition of HE and cartridge designs, it is possible to create plasma jets, with the parameters, allowing their usage for PA.

The concept of a four-beam plasma antenna design is developed. Results of the laboratory and explosive tests are addressed.

The explosive testing results demonstrated that this antenna allows to obtain up to $6 \div 7$ dB gain over the range of frequencies $600 \div 800$ MHz.

Undertaken results analysis has shown, that the obtained characteristics can be drastically improved by optimizing HE chemical composition and cartridge design.

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