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Ultra-wideband antenna for recording radio emission in the initial phase of a high-voltage laboratory atmospheric discharge

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A compact ultra - wideband antenna, designed for the employment in the experiments on studying radio emission generated in the initial phase of the spark discharge, is presented. A flat type of antennas based on an expanding slit (Vivaldi antenna) is considered. The simulation and calculation of the antenna parameters are carried out. The results of using the antenna in laboratory experiments are demonstrated. It is shown that the generation of the highest frequency part of the radio emission spectrum coincides with the pre-breakdown stage of the discharge, before a sharp increase in the current starts.

Keywords: Vivaldi antenna, microstrip antenna, radio emission, antenna simulation and calculation, atmospheric spark.

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Introduction

The study of processes in an atmospheric discharge leading to the generation of radiations of various types (X-ray, microwave, neutron, etc.) is important for the development of fundamental and applied physics of gas discharge. The generation of microwave radiation is of particular interest. A comprehensive study of this phenomenon will allow to better understand the processes proceeding at the initial stage of a discharge, during the first nanoseconds after high voltage is applied to electrodes. Development of analysis methods of this radiation will make it possible to create, in particular, lightning direction finders of a new type, operating in the range from hundreds of MHz to ten GHz, as distinct from up-to-date samples (10–60 kHz). This will enable thunderstorm activity areas to be determined more accurately, which is of great importance, for example, concerning a safety of air traffic.

Generating the radio-frequency radiation when forming natural lightnings at the frequencies above 500 MHz was registered for the first time by Takagi and Takeuchi in 1963 [1], and then by Brook and Kitagawa in 1964 [2], who reported on the observation of the radio-frequency radiations at a frequency of 0.85 GHz with a bandwidth of 200 kHz, claiming that the observed radiations coincide with a negative stepped leader stroke, back stroke, lightning leader stroke. At the moment in-situ measurements of radio-frequency radiations are carried out from the negative stepped leaders of lightnings in the range of 1.5–1.6 GHz [3]. The radiation was observed using a ceramic microstrip antenna and a digital radio receiver tuned to a central frequency of 1.63 GHz with an operating bandwidth of 2 MHz.

In laboratory conditions this problem is also still being investigated nowadays. The authors of works [4,5] were able to register radio-frequency radiation pulses with a frequency of 2.4 GHz, a maximum power of which coincided with a moment of generation of the X-ray radiation (XR). High-frequency radio-frequency radiation maxima, as well as XR [6] pulses, were also observed in the discharges without a breakdown (incomplete discharges), which may be evidence of a similarity of their generation processes.

The numerical simulation of streamer propagation and merging in lightnings conducted by the [7] authors in the case of an over-breakdown field $E_0 = (1.5-2) \cdot E_k$, where E_k is a breakdown field, showed the possibility of effective generation of electromagnetic radiation in the range from ten MHz to units of GHz and higher. And if the radiation on the order of ten MHz, usually used in thunderstorm direction-finding systems, is associated with the already known physical processes of streamer propagation arising in a stepped leader stroke corona during a clear air breakdown, then the radio-frequency radiation in the range of hundreds of MHz to ten GHz can give an opposite collision of streamers due to a rapid current rise.

Similar results on the radio-frequency radiation generation in the range from tens of MHz to several units of GHz were obtained on streamer collisions under a normal atmospheric pressure in the case of a sub-breakdown field $E_0 < E_k$ [8].

In this case, ordinary exponentially growing streamers can effectively generate the radio-frequency radiation in the range of 3–300 MHz [9], but a radiation at higher frequencies is negligibly small, since a time constant of their growth is on the order of nanoseconds. Therefore, it is important to identify correctly the processes that can lead to very rapid changes in current necessary to generate the radio-frequency radiation of appropriate frequency ranges.

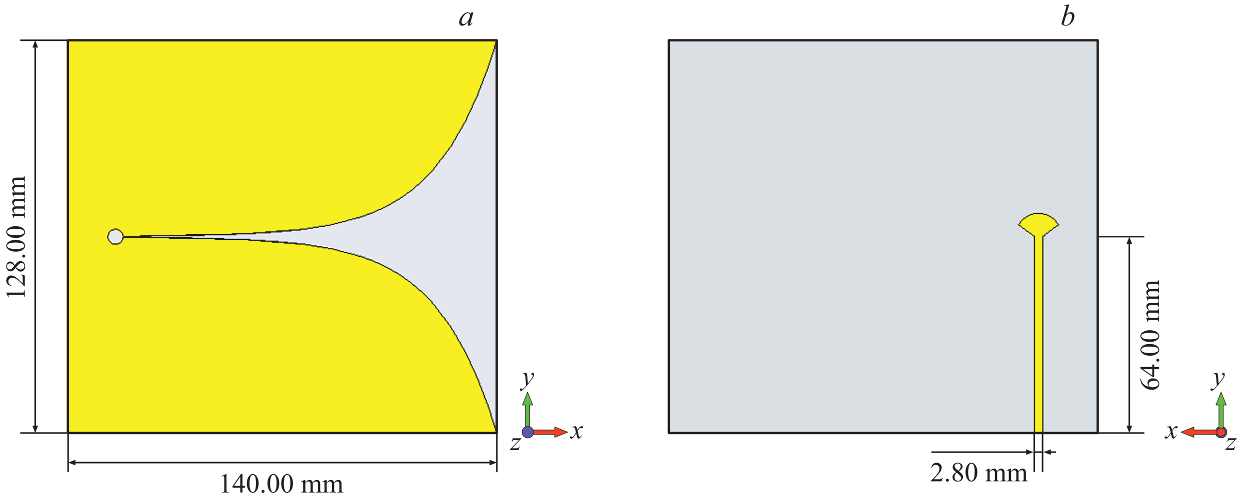

Figure 1. View of design model of antenna with dimensions: *a* is a „front" side with a working area and resonator, *b* is a „reverse" side with a microstrip line.

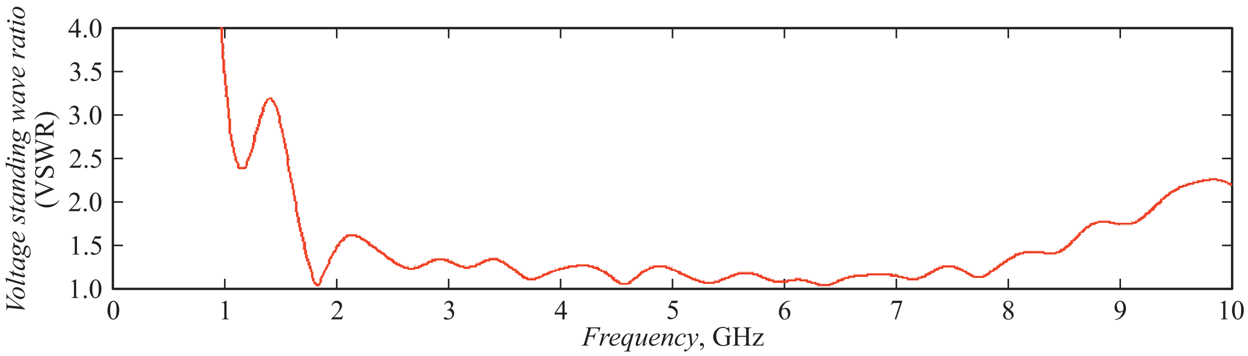

Figure 2. Voltage standing-wave ratio.

Unfortunately, the study of generation of broadband radio-frequency radiations during developing atmospheric discharges in nature seems to be a rather difficult task. A thunderstorm activity occurs for only a few weeks per year. At the same time, in order to collect sufficient statistics, recording equipment must be located as close as possible to a thunderstorm front, which is continuously moving. As a separate problem, a study of the radio-frequency radiation of centimeter range and to be brief due to the peculiarities of propagation of these waves in a medium can be singled out.

Nevertheless, it can be assumed that the processes in a discharge, leading to the generation of corresponding radiation, are of fundamental nature. In this regard, the study of forming microwave discharges accompanied by an emission in small air spaces can throw light on generation mechanisms of other accompanying radiation. In the present work, the microwave generation in a laboratory spark discharge with a 5 mm space between electrodes having a needle-plane shape was investigated through an example of discharges in small spaces. The radio-frequency radiation spectra taken at various stages of forming a spark discharge are presented. They show that the developed antenna is suitable for analyzing the physical processes generating the microwave radiation in a laboratory spark plasma, and in the future it will help to draw conclusions on the nature of these phenomena.

1. Observation equipment

An ultra-wideband antenna based on an expanding slot line (Vivaldi antenna) was developed for registering the radio-frequency radiation generated during the initial phase of a high-voltage spark discharge. The Vivaldi antenna (VA) of a coplanar type (Fig. 1) is a dielectric substrate, one side of which is covered by a metallization layer in the form of an expanding slot. This type of antennas was chosen for a variety of reasons: a wide frequency range (bandwidth), simplicity of calculation and manufacturing, small size. Low amplification (on the order of 6-8,dB) can be compensated by placing the antenna at a distance of 3–5 m from a discharge. This will allow to be already in a

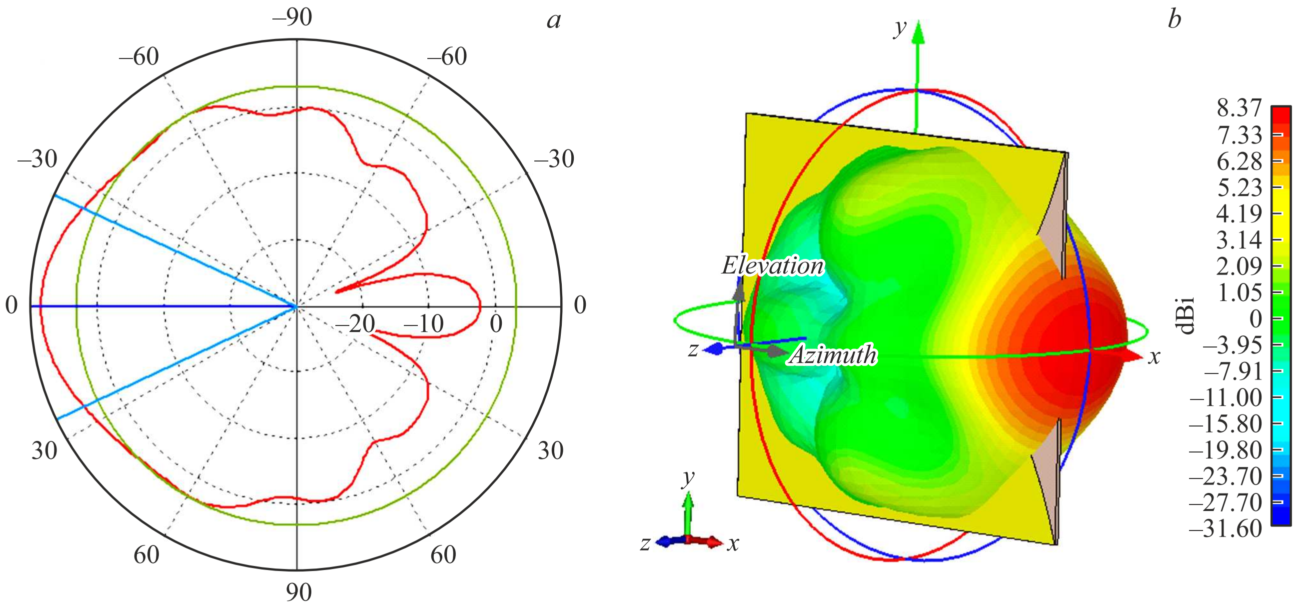

Figure 3. Directional pattern on a frequency of 3.5 GHz: *a* — in plane XZ, *b* — 3D.

„distant zone“, while a radio-frequency radiation power will remain sufficient for its registration by this type of antennas.

Simulation and calculation of antenna parameters were performed using a CST microwave studio software package. Structurally, the antennas are made in the form of printed copper conductors on FR-4 fiber-glass plastic 1.5 mm in thickness. The material has a dielectric permittivity coefficient $\varepsilon = 4.5$ (measured at 1 MHz) as well as good strength and cost characteristics. A thickness of the copper layer on each side is $45\,\mu$m. The dielectric loss tangent, which reaches a value of 0.025 on the frequencies of the order of 1 GHz and above, may be included in disadvantages of FR-4. This negatively affects the amplification factor. But the dielectric losses are taken into account when simulating and calculating the antenna, and the antenna characteristics that meet the requirements of experiments being conducted are obtained with their account.

Based on an analysis of the works [10,11], the VA aperture is made in the form of an exponentially expanding slot, $U_y = s\exp(rx)$, where $s = 0.25$ mm is a width of the slot at its base, x is a coordinate along the antenna axis, $k = 0.05198$ is a curvature factor, whose value was selected empirically.

Matching of a wave impedance of the VA slot with a 50-Ohm transmission cable is implemented at the expense of a microstrip line. Calculation of satisfactory parameters of impedance and matching of the microstrip line with the antenna slot in the excitation point were implemented using a standard function built into a used calculation program. To improve the matching parameters, an enlargement at the end of the microstrip line and a resonator 10 mm in diameter on „the front“ side of the antenna were used.

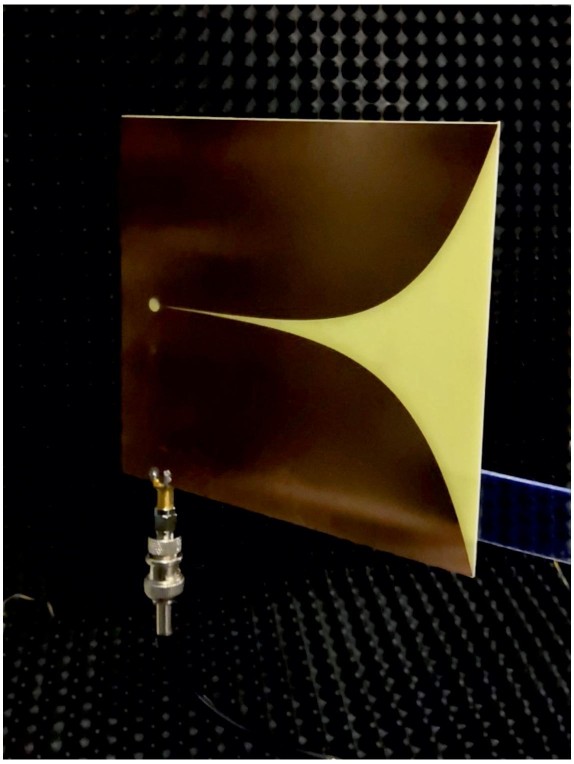

Figure 4. Appearance of developed VA.

Simulation of variants of different antenna geometries was performed in several iterations with an increasing accuracy and density of a computational grid, which showed a convergence of results when decreasing a cell size. The results presented below are carried out for the grid divided with parameters$699 \times 674 \times 46$ of cells. The optimized

Characteristics of developed VA

Operating frequency range	1.66–9.36 GHz
Polarization	Linear
Standing-wave factor in operating frequency range	Not more than 2.0
Amplification factor	Not less than 6 dB with an unevenness of no more than 2 dB in the operating angle cone ±25°
Operating temperature range	From −50°C to +80°C
Overall dimensions	140 × 128 × 1.55 mm

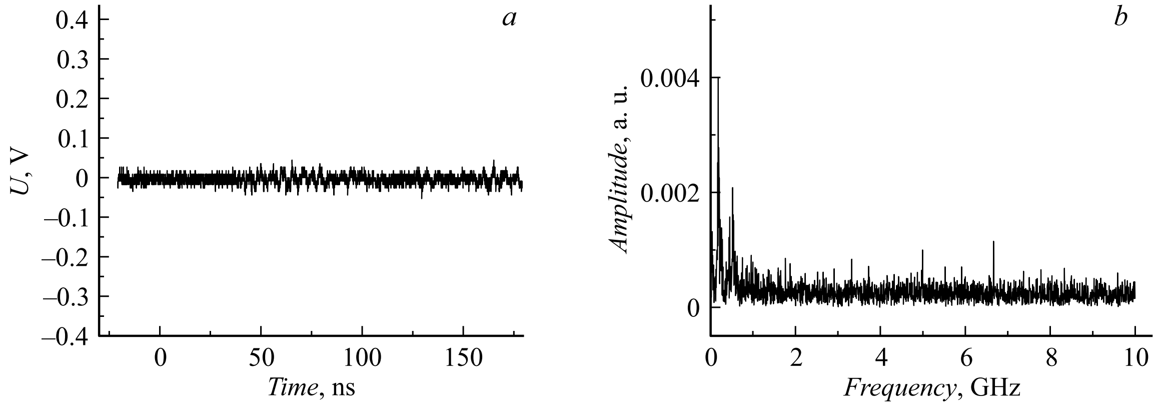

Figure 5. *a* is an example of a signal received from the antenna in the absence of flowing the main discharge current , *b* is a spectrum of this signal.

variant has a designed standing-wave factor required in laboratory measurements in the frequency range from 1.66 to 9.36 GHz (Fig. 2). A directional pattern of the antenna is shown in Fig. 3.

The antenna was manufactured by milling foil-coated fiber-glass plastic on a CNC machine. To pick up a signal from the antenna an SMA connector is used (Fig. 4). The main antenna characteristics are given in the table.

2. Verification

The developed antenna was used to register the radio-frequency radiation in a laboratory spark discharge with a 5 mm gap between the electrodes having a needle-plane shape.

The antenna was installed at a distance of three meters from a laboratory spark. A radio-frequency signal from the antenna was registered by a LeCroy WM 8620A oscilloscope with a bandwidth of 6 GHz. The radio-frequency signal is transmitted to the recording equipment through an LMR-400 coaxial cable 3 m in length. This type of the cable differs from analogs by a good cable screening (not less than 90 dB) and low levels of losses in the cable: for a frequency of 1.5 GHz–0.168 dB/m; for 1.8 GHz–0.186 dB/m; for 2.0 GHz–0.196 dB/m; for 2.5 GHz–0.222 dB/m; for 5.8 GHz–0.355 dB/m. Thus, the

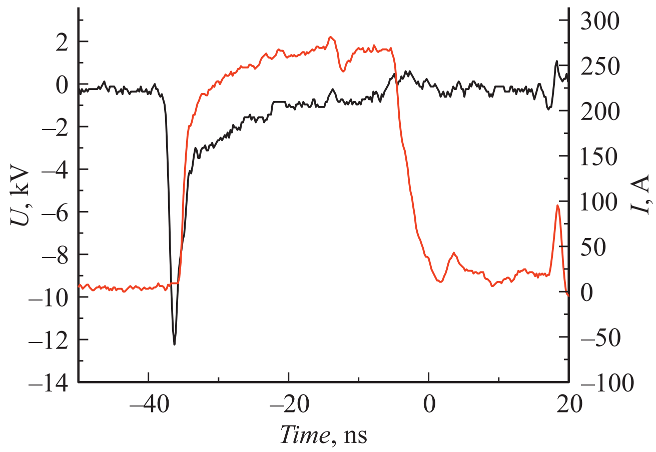

Figure 6. Discharge characteristics: voltage (from the left, black) and current (from the right, red).

losses in the cable in the range of operating frequencies of the antenna do not exceed 1–2 dB.

To assess an effect of electromagnetic interference on the cable as well as an influence of echo conditions in a laboratory and secondary signals received by the antenna, a series of experiments with applying a pulse voltage to the high-voltage electrode at no-load (in „idle“ mode) was

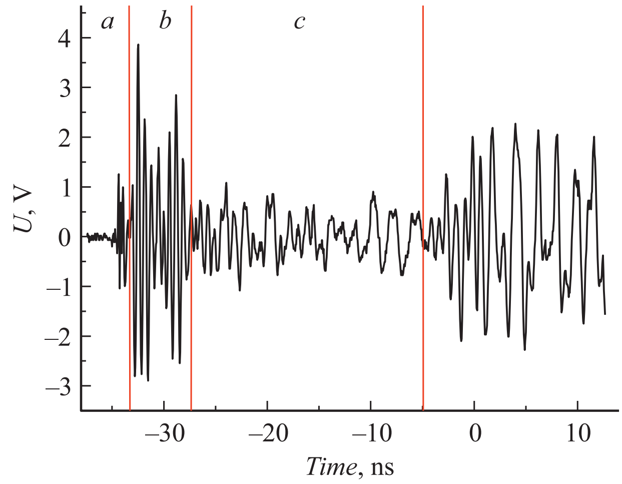

Figure 7. Example of the signal received from antenna: *a* is a pre-breakdown stage, *b* is a breakdown stage, *c* is a main discharge current flowing stage.

carried out. In this configuration, it is seen that when operating all the equipment and a voltage generator in the absence of flowing a main discharge current, the high-frequency radio-frequency radiation is absent (Fig. 5).

In the experiment with a high-voltage discharge in the needle-plane interspace 5 mm in length with a typical volt-ampere characteristic shown in Fig. 6, generation of the HF radio-frequency radiation was detected using the developed VA. An example of registered radio-frequency signals is shown in Fig. 7. An amplitude spectrum of the radio-frequency signal obtained using the fast Fourier transform (FFT) is presented in Fig. 8, *a*.

The three characteristic time zones corresponding to different stages of discharge evolution in the interspace being studied can be distinguished in the obtained signal. The first zone is a pre-breakdown stage (before the current rises sharply), characterized by an applied high voltage. In this stage, avalanches of electrons appear during an explosive emission and streamers are formed. Evolving, they begin to ionize the environment along the way of their passage. A surge of the highest-frequency component of radio-frequency spectrum (up to 6 GHz, Fig. 8, *b*) can be observed in this stage. The second zone is characterized by a voltage drop and a current rise this is a stage of evolution of a highly ionized spark [15] after the moment of electrical breakdown of the interspace. A spectrum of the radio-frequency radiation at this stage of discharge is shown in Fig. 8, *c*. A signal amplitude increases in comparison with the pre-breakdown stage, while a main contribution is made by the high-frequency radiation on the frequencies 1.4–1.8 GHz, which indicates a complexity of processes of forming a resulting spark. The plasma formation processes begin to include, in addition to the medium ionization by

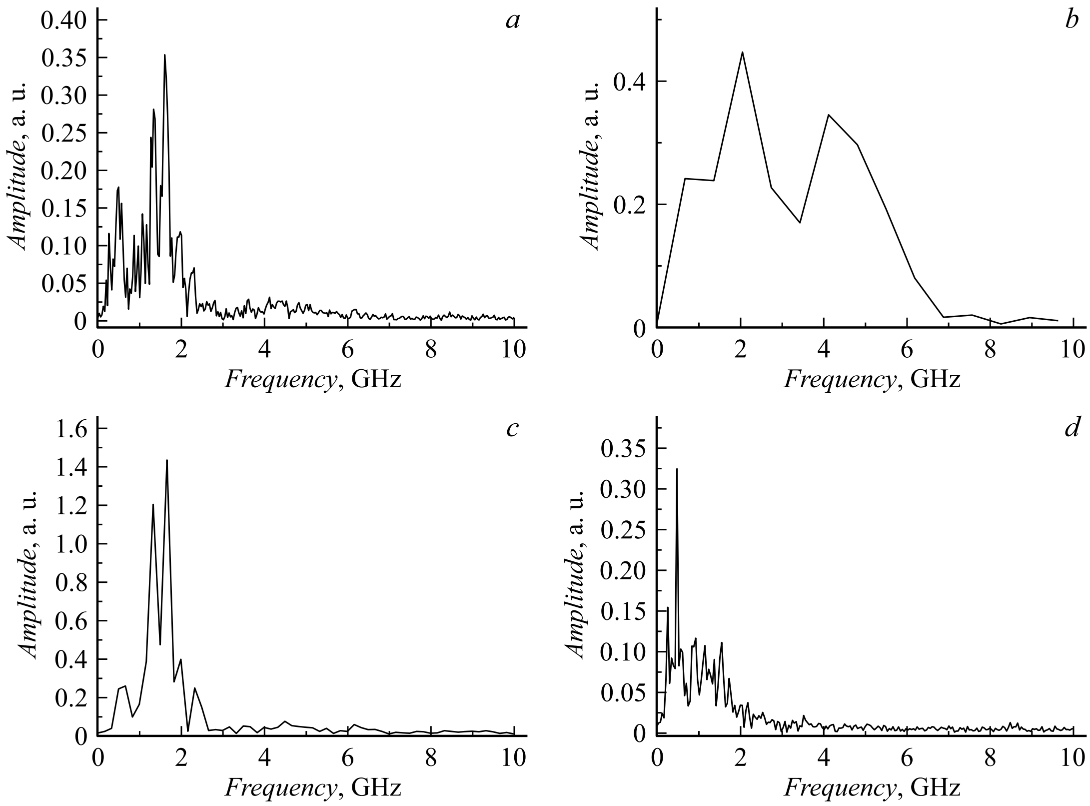

Figure 8. Radio-frequency radiation spectra: *a* is a common spectrum of the entire discharge, *b* is the first zone, **c** is the second zone, *d* is the third zone.

electron avalanches, a rapid increase of conductivity in the growing channel consisting of highly ionized filaments [15]. The third zone is a stage of main discharge current flowing, when the electrodes are connected by the resulting spark channel. It is characterized by a high radiation intensity in the range of 200−500 MHz, a spectrum of this zone is shown in Fig. 8, *d*. Perhaps this is due to plasma oscillations in a highly ionized spark.

Conclusion

Calculation, simulation, and development of an ultra-wideband antenna with an expanding slot for use in experiments on the registration of the radio-frequency radiation generated during the initial phase of spark discharge are proposed in this work. An antenna with an operating frequency range of 1.66−9.36 GHz with a voltage standing-wave ratio not exceeding 2.0 has been manufactured. Results of using the antenna in laboratory studies have been presented. Radio-frequency radiation spectra at various stages of forming a spark discharge have been obtained.

An analysis of the obtained radio-frequency radiation spectrum makes it possible to single out different stages in the evolution of the spark discharge. Further development of the antennas will help in obtaining a quantitative information about plasma processes. The results in the first approximation are in agreement with experimental and analytical works on a study of lightning and laboratory spark discharges.

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Conflict of interest

The authors declare that they have no conflict of interest.

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