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04

Spectral characteristics of microwave emission of a high-voltage extended atmospheric discharge based on wavelet analysis

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A spark discharge at the pre-breakdown stage is a source of high-power microwave pulses. The Morlet wavelet transform was used for frequency-time localization of high-amplitude bursts. Exponential approximation was used to characterize quantitatively the signal dynamics. It provided an opportunity to determine the key parameters: initial amplitude α and attenuation rate β. Two groups of flares differing in their attenuation nature were identified by processing the experimental data. Statistical analysis revealed a discrepancy between the distribution of coefficients and the normal law, which underscores the stochastic nature of processes. The results of this study contribute to a deeper understanding of the mechanisms of microwave radiation generation in electric discharge systems.

Keywords: wavelet analysis, radio emission, atmospheric spark discharge, streamer.

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The study of microwave signals accompanying atmospheric electrical discharges remains relevant and is of academic interest for the physics of gas discharge processes; in addition, such research has practical implications [1,2]. It has been suggested in modern studies, which include experimental recording of microwave signals from atmospheric discharges in natural and laboratory conditions and numerical modeling, that pulsed microwave radiation is produced as a result of collisions of counter-directed streamers. It is assumed that these collisions create regions with high electric fields, where rapid current switching (capable of generating microwave radiation) is possible [3–5].

Beam-plasma instabilities are assumed to be formed in the discharge gap in the region of interaction of counter-directed streamer coronas, where microdischarges act as a saturation mechanism for these instabilities [6]; notably, this process may be non-instantaneous and decay with time, generating repeating pulses of radio emission. Although a number of theoretical and experimental papers have been published, the temporal characteristics of microwave signals arising from collisions of counter-directed streamers remain underexplored.

In the present study, we propose an approach to analyzing the temporal structure of microwave signals produced in atmospheric discharges that are initiated by an experimental setup designed for studying an extended spark discharge in air. This setup allows one to form meter-scale spark discharges at a voltage of approximately 1.2 MV [7]. The scale of the setup, the electrophysical discharge parameters, and the diagnostic equipment provide an opportunity to resolve temporally individual events evolving on a time scale on the order of 1 ns at the stage of interaction of counter-directed streamer coronas. An approach utilizing wavelet analysis, which makes it possible to localize the time and frequency parameters of microwave signals, is proposed to be used for analysis of these signals. The main result of this study is the identification of characteristic structures in a signal and the development of a method for their description with approximation by exponential functions.

Continuous wavelet transform (CWT) is an efficient method for analysis of non-stationary microwave signals:

$$W_\psi(a,b)=\frac{1}{\sqrt{|a|}}\int_{-\infty}^{\infty} f(t)\psi^*\left(\frac{t-b}{a}\right)dt. \qquad (1)$$

It allows one to study the frequency and time characteristics of a signal simultaneously by projecting it onto a family of functions obtained by scaling and shifting mother wavelet ψ [8,9]. In formula (1), a is the scale parameter that sets the frequency resolution, b is the time shift parameter, and ψ^* is the complex conjugate function of the mother wavelet [8,9].

The Morlet wavelet, which is an effective tool for analysis that provides high frequency-time resolution due to its narrow-band structure and exponentially modulated shape, was used to analyze the microwave signal. Its similarity to harmonic oscillations makes this wavelet optimal for identifying and localizing high-frequency components in non-stationary processes:

$$\psi(t)=\pi^{-\frac{1}{4}}e^{i\omega_0 t}e^{-\frac{t^2}{2}}, \qquad (2)$$

where ω_0 is the center frequency. Scalograms obtained using the Morlet wavelet (Fig. 1) feature clearly defined bursts of high-frequency radiation that are localized in both time and frequency. Marked points correspond to the maximum frequencies of signal components that determine the spectral width at each moment in time. These frequency maxima may be regarded as nodes for further approximation.

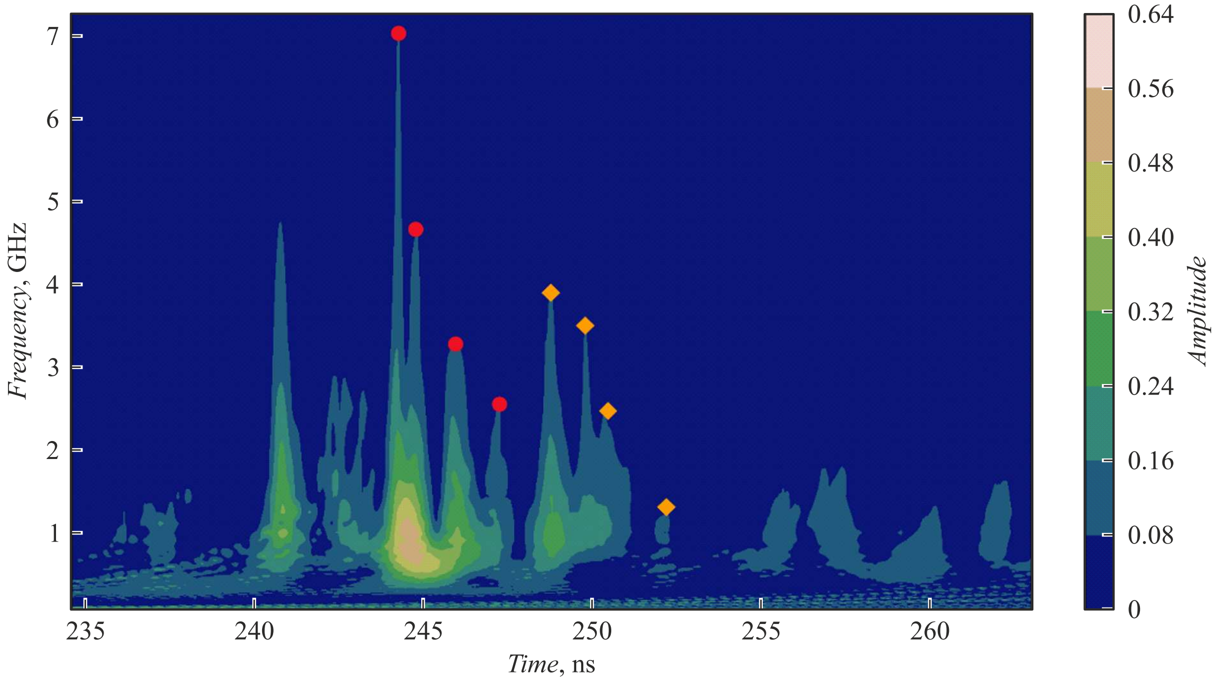

Figure 1. Scalogram of a section of a microwave signal with pronounced high-frequency signal peaks. Marked points correspond to the frequency maxima used to approximate the decaying signal. Symbols represent different decaying objects: the first group of events is marked with circles, while the second group of events is marked with diamonds.

The study is aimed at testing the hypothesis regarding the properties of flare structures (peaks) that emerge when counter-directed streamers collide at the pre-breakdown stage of a spark discharge. According to this hypothesis, the frequency-time parameters of flares may be approximated by exponential function

$$f(t) = \alpha e^{-\beta t}, \tag{3}$$

where α is the amplitude of the approximating function, which is determined by the spectral width of the first peak in each group of points in the scalogram, and β is the attenuation coefficient that characterizes the rate of amplitude reduction with time.

Vivaldi ultra-wideband antennas operating within the centimeter range and providing reception at frequencies above 1 GHz were used to detect microwave discharge emission. These antennas were mounted at a distance of 3 m from a laboratory spark. The radio signal from the antenna was recorded using a LeCroy WM 8620A oscilloscope with a bandwidth of 6 GHz. An SF-141 FEP cable 3 m in length was used for signal transmission to the recording equipment. High-frequency attenuators operating at frequencies up to 18 GHz at an SWR (standing wave ratio) < 1.35 and an attenuation of 20 dB were installed at the oscilloscope input; a more detailed description of the setup was given in [10,11].

The initial phase of an extended high-voltage discharge is of prime interest in the present study. It is at this stage that intense generation of broadband radio radiation with high and ultra-high frequencies, active reproduction of numerous streamers of opposite polarity, and bursts of radiation power reaching characteristic frequencies of 1–6 GHz (Fig. 2) are observed. The maximization of voltage in the discharge gap, which correlates with the onset of high-frequency radio emission, is an important feature of this stage. The timeline of discharge development was detailed in [12].

It follows from the analysis of the frequency-time characteristics of the microwave signal that the shape of flares seen in the scalogram (Fig. 1) may be characterized correctly by an exponential dependence (formula (3)). To illustrate this method, two groups of peaks (circles and diamonds) are highlighted in the scalogram. Marked points correspond to the nodes of approximating exponential curves. A total of 300 microwave signals obtained in laboratory conditions were analyzed in the present study. Groups of flares corresponding to the development stage of an atmospheric discharge of interest were analyzed in each signal. The results of application of the approximating exponential functions are presented in Fig. 3.

The next phase of the study was the analysis of coefficients of the exponential approximating functions applied to the identified curves in the microwave signal. Coefficients α and β were determined for each approximating function. The obtained coefficient values were presented in the form of a scatter plot (Fig. 4, a) in order to analyze the distribution of parameters and search for patterns in their variation.

Figure 4, a shows the distribution of coefficients of the approximating functions with two pronounced different

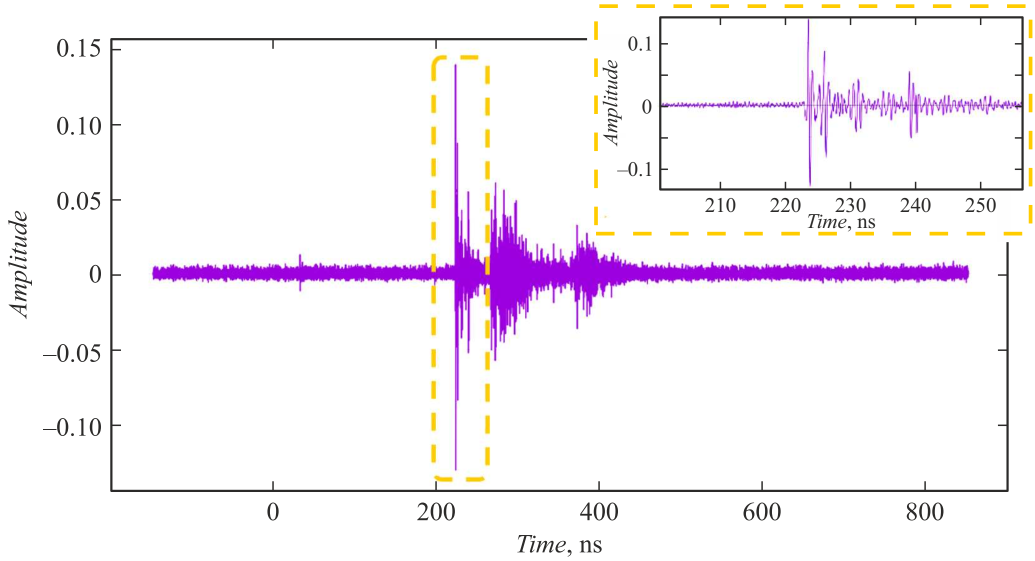

Figure 2. Signal within the 1–6 GHz range reconstructed using the wavelet transform. The studied time section of the microwave signal is highlighted by a dashed rectangle and corresponds to the pre-breakdown stage of a spark discharge.

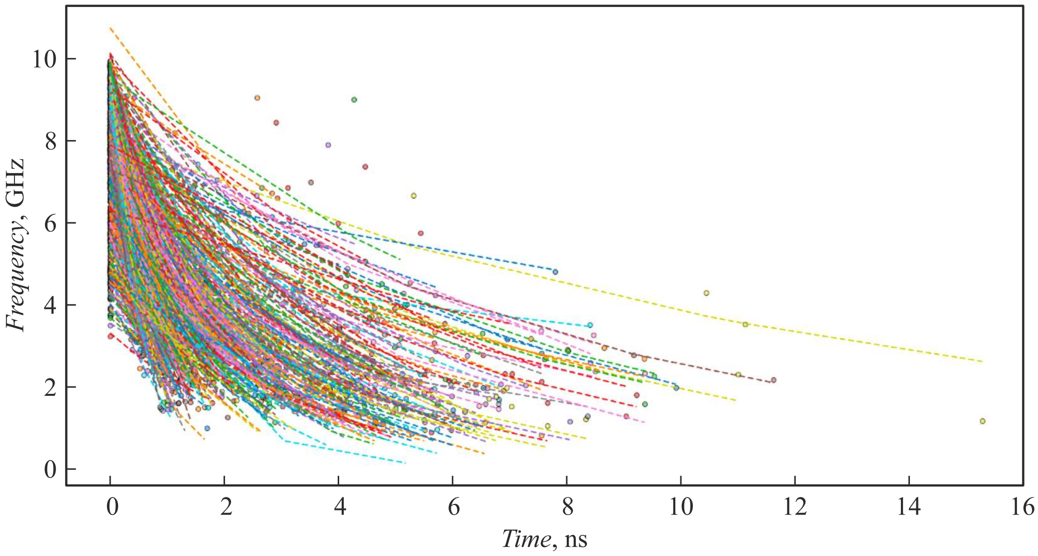

Figure 3. Approximation of signal curves with an exponential function.

directions characteristic of exponential approximation. The first group (highlighted by a purple oval) is characterized by a sharp increase in β with increasing parameter α, which may be indicative of more intense attenuation. The second group (yellow oval) is characterized by a weak dependence of coefficient β on parameter α. This behavior suggests a tendency toward stabilization of processes in this category of flare objects within the microwave signal range.

Having analyzed the distribution of approximation coefficients, we formulated the following hypotheses. First, the observed patterns may arise due to the presence of two different microwave signal generation mechanisms that determine the dynamics of the spectral peak width within each group. Second, this may be indicative of a heterogeneous nature of flare events: some of them may be generated as a result of fast local processes, while the evolution of others may be associated with slower and more global processes in discharge plasma.

The results of analysis of the distribution of approximating coefficients are presented in Fig. 4, *b* in the form of histograms. It is evident that the empirical distributions of approximation coefficients deviate from the normal distribution. This deviation is indicative of complexity and nonlinearity of the processes that shape the dynamics of flare structures. This observation proves that simplified statistical models based on the assumption of normality are inapplicable, suggesting that more complex models incorporating the combined influence of numerous factors need to be developed in order to characterize adequately the pre-breakdown discharge stage.

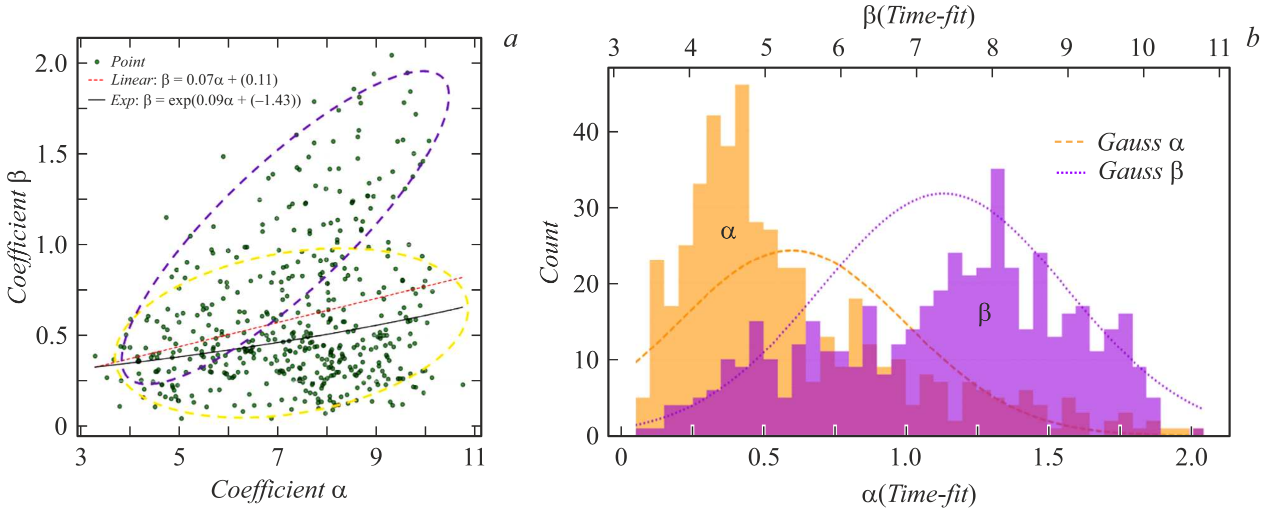

Figure 4. *a* — Scatter plot of coefficients of approximating exponential functions. Dotted and solid curves represent linear and exponential trend lines, respectively. Ovals highlight two groups of points with different attenuation rates: the amplitude decreases rapidly in one group and slowly in the other. *b* — Histograms of coefficients α and β of the approximating exponential functions; curves correspond to a normal distribution. A color version of the figure is provided in the online version of the paper.

The main objective of the study was to analyze flare structures in microwave signals at the pre-breakdown stage of a spark discharge, which are characterized by short-term high-amplitude bursts with clear localization in the time and frequency domains. Wavelet analysis, which provides accurate time-frequency localization, was used to identify them. The dynamics of flares was characterized via exponential approximation. This allowed us to estimate quantitatively the initial amplitude of the approximating function, which characterizes the spectral width of each group of peaks and the attenuation rate, and to perform their statistical analysis.

Exponential approximation provided an opportunity to characterize each burst quantitatively using coefficients α (initial amplitude) and β (exponential attenuation rate). Analyzing the distribution of these coefficients, we revealed patterns in correlation between α and β (with the time interval taken into account).

This approach revealed that the observed flare objects may be divided into two groups differing both in amplitude and in the nature of attenuation. One group is characterized by a rapid signal decay at high values of the approximating function amplitude, while the other is characterized by a smoother and more stable attenuation with a less pronounced amplitude dependence of the decay rate. These differences may be indicative of the presence of different physical mechanisms of formation of flares.

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Conflict of interest

The authors declare that they have no conflict of interest.

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