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Microwave diagnostics of electrical discharges in an artificial cloud of charged water drops

© N.A. Bogatov,[2] V.S. Syssoev,[1] D.I. Sukharevsky,[1] M.Yu. Naumova[1]

[1] Federal State Unitary Enterprise ?Russian Federal Nuclear Center „Zababakhin All?Russia Research Institute of technical Physics“,
143500 Istra, Moscow region, Russia
[2] Institute of Applied Physics, Russian Academy of Sciences,
603950 Nizhny Novgorod, Russia
e-mail: v.s.sysoev@vniitf.ru

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The microwave diagnostics of discharges occurring in an artificial cloud of charged water droplets created in an open air simulating the environment of thunderclouds is implemented. An artificial cloud with a droplet size of about 1 microns is opaque in the visible range, so intra-cloud discharges are not available for investigation by traditional methods in the spark discharge physics based on the registration of visible discharge radiation. Microwaves pass through such a cloud without noticeable attenuation, they interact only with the plasma of discharges occurring in the cloud. The probing microwave radiation had a wavelength of 8 mm. The attenuation of microwaves passed through the cloud was measured with temporary resolution of about 10 ns. The temporal characteristics of intra-cloud discharges were investigated.

Keywords: spark, leader, streamer, electromagnetic wave.

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Introduction

Thus far a lightning remains an understudied natural phenomenon, despite two hundred years history of intensive studies. Traditional methods of studying the lightning, as well as long spark discharges, in many aspects modeling the lightning, are based on registration of visible radiation, emitting by these discharges [1–3]. However, in cloud environment the visible radiation strongly dissipates, therefore the discharge processes inside thunderclouds are unavailable for traditional methods of lightning discharges observation. Field experimental studies directly inside the thunderclouds are associated with the large technical difficulties, therefore they are very rare and have limited possibilities. For studying the discharge processes in cloud environment in laboratory conditions the artificial clouds of charged water droplets are created [4,5], and these droplets are electrified so much, that between these clouds and grounded surfaces, as well as inside the clouds, the electrical discharges appear. Two such generators of the charged clouds are currently operated in All-Russia Research and Development Center „Russian Federal Nuclear Center – Zababakhin All-Russia Research Institute of Technical Physics“. The average radius of droplets in these clouds is about $0.5\,\mu$m. Such droplets efficiently dissipate the visible range light, therefore application of optical study methods, traditional for spark discharge physics, for studying the discharges inside such clouds is impossible for the same reason, for which the discharges inside thunderclouds remain understudied, — the discharges are not visible. In the works [6–8] for discharges observance inside the artificial cloud the infrared (IR) camera with spectral sensitivity range of $2.5-5.5\,\mu$m was used. IR radiation wavelength is significantly bigger than artificial cloud droplet size, therefore IR radiation scattering is not so significant, as for visible light. Therefore, IR images of the intracloud discharges were successfully observed. Disadvantage of this method of intracloud discharges study consisted in low IR camera speed. Exposition time (2−3 ms) significantly exceeded the duration of the whole discharge process, therefore it was impossible to see the discharge dynamics. In this work the microwave diagnostics with high time resolution was used for intracloud discharges study. Microwave radiation is almost not dissipated with micron size droplets, but can absorbed and dissipated with a plasma, appearing at discharge processes inside the cloud. Intensity of intrinsic microwave radiation from discharge plasma is not sufficient for reliable registration under conditions of high level of electromagnetic disturbances, characteristic for high voltage experiment. This requires to use an active microwave diagnostics, probing the cloud with microwave beam. It should be noted that there are not that many studies of long spark discharges using the active methods of diagnostics. For registration of reduced density of gas in spark channels due to gas heating the schlieren method [9–17] and interferometric method [18–20] were used. In the work [21] the active method of microwave diagnostics was used for the first time for studying the laboratory long spark discharge, excited in the rod-plane gap with megavolt voltage pulse. In this work the microwave diagnostics, similar to the one, used in [21], was implemented and used for studying the long spark discharges inside laboratory artificial electrified cloud. The microwave diagnostics of the discharges in artificial charged cloud, created in this work, had time resolution of 10 ns. Application of this technology allowed to observe time characteristics of intracloud discharges development.

1. Description of experiment and microwave diagnostics

Scheme of the experiment is presented in Fig. 1. The artificial cloud was formed as a result of condensation of water steam, coming from the steam generator through a nozzle, located in the center of the grounded flat electrode with diameter of 3 m. Electrification of droplets, formed in the steam flow, was performed by means of corona discharge on a needle electrode located in the nozzle. The detailed description of the unit for creation of the artificial charged cloud is presented in [6]. Average radius of droplets, evaluated based on measurements in the work [22], in our experiments was about 0.5 μm [6]. The charge of the cloud, at which the discharges start, was estimated to be about 60 μC [6]. Other cloud parameters, such as droplets concentration and distribution by charges and masses, are unknown.

In this work the scheme of microwave diagnostics, simplest in implementation, was used: attenuation of microwave beam, passing though the cloud with ionization, was registered. Generator G4-91, loaded on the horn antenna, was a source of microwave radiation. The generator worked in continuous mode. Generator output power was 5 mW, radiation frequency — 37 GHz, output power fluctuations level — 10^{-3}. Convergent Gaussian microwave beam was formed by dielectric lenses in such way, that the beam waist was approximately in the center of the cloud in the place of the most intense discharges. Diameter of microwave beam in the waist at $1/e$ intensity level was $\sim$ 10 cm (intensity distribution in the cross section of the beam in the waist, close to Gaussian, was measured with microwave diode). The shape of the microwave beam between the visible cloud boundaries was almost cylindrical (at the cloud boundaries the calculated width of the beam was by 3% larger than in the waist). The distance from microwave beam axis to the grounded plane was 1.35 m. The polarization of the microwave radiation was linear, perpendicular to the grounded plane. The microwave beam, passed through the cloud, was focused with a lens to the open end of the receiving waveguide, and then amplified with 20 dB amplifier and detected with microwave diode D404 with linear volt-watt characteristic and time constant of 10 ns. The output signal from the microwave diode was recorded with an oscilloscope. The feature of the high voltage experiment is a presence of large electromagnetic interference to measuring equipment during spark discharge, therefore it was necessary to screen both radiating and receiving parts of the measuring equipment. For that purpose the microwave generator was put into screened room, while receiving part of the equipment was put into closed metal container with self-contained power supply to prevent from disturbances over the wires.

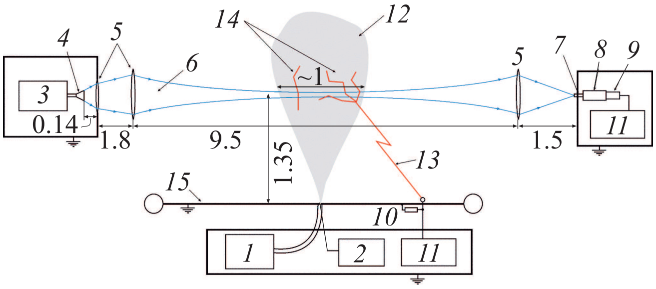

Figure 1. Scheme of the experiment and microwave diagnostics (distances are specified in meters): *1* — steam generator, *2* — high voltage power source, *3* — microwave generator, *4* — horn antenna, *5* — lenses, *6* — microwave beam, *7* — receiving waveguide, *8* — microwave amplifier 20 dB, *9* — microwave detector, *10* — measuring ohmic low-inductive shunt, *11* — oscilloscope, *12* — charged aerosol cloud, *13* — spark cloud-ground, *14* — discharges (and discharges parts) inside the cloud, *15* — grounded plane.

The attenuation of microwave radiation, caused by the cloud in the absence of electrical activity, was lower than sensitivity threshold of our diagnostics. The relative attenuation of microwave radiation in the cloud was defined as a difference of unit and ratio of microwave diode output signal and its level in the absence of the cloud or electrical activity in the cloud.

The sensitivity of our microwave diagnostics was defined with the level of fluctuations of the microwave generator output power. The minimum level of the registered relative attenuation of the microwave radiation, passed through the cloud, was 10^{-3}.

2. Attenuation of microwave radiation in the area, occupied by spark discharge

Long spark discharges always create length plasma channels of almost round cross section, diameter of which is much lower than their length. Therefore, the scattering and absorption of electromagnetic wave, incident to spark channel, by some channel section can be assumed almost the same, as for round cylinder of infinite length and with the same diameter as the plasma channel. Channels of long sparks are mainly oriented along the electric field. In our experiment the electric field of the charged cloud and discharges in it were mainly oriented normal to the grounded plane, almost like polarization of the probing microwave radiation. Therefore, the interaction of microwave radiation with plasma channels of intra-cloud discharges in our experiment is closest to the problem of diffraction of the flat linearly polarized electromagnetic wave on round infinite plasma cylinder, axis of which is parallel to electric field vector in the wave.

2.1. Microwave radiation absorption with streamers

The problem of diffraction of the flat linearly polarized electromagnetic wave on the round cylinder of low-ionized air plasma (vector of electric field of the wave is parallel to the cylinder axis) was examined in [21]. It was shown, that, if in atmosphere air under normal conditions the radius of plasma cylinder r and concentration of electrons in it n satisfy the condition

$$nr^2 \ll 1.2 \cdot 10^{13}\,\mathrm{cm}^{-1}, \qquad (1)$$

then the following statements are true:

1) intensity of millimeter range electromagnetic wave absorption is much higher than scattering intensity;

2) amplitude of scattered wave on cylinder surface is much less than the incident wave amplitude, therefore the amplitude of high-frequency electric field on cylinder surface is almost equal to the incident wave amplitude;

3) thickness of skin-layer inside the cylinder is much bigger than its radius, therefore the electric field inside the cylinder is almost homogeneous and equal to the incident wave field.

Characteristic parameters of the streamer channels plasma [1], $n \leq 10^{14}\,\mathrm{cm}^{-3}$, $r \leq 1\,\mathrm{mm}$, satisfy the condition (1), therefore attenuation of microwave radiation, passing through the streamer discharge, is almost equal to power, absorbed with all free electrons of the streamers, located in the incident microwave beam. Power, absorbed with a single free electron in gas, located in the high-frequency electric field with amplitude E, is equal to [23]

$$w_e = \frac{e^2 \nu_e E^2}{2m(\nu_e^2 + \omega^2)}, \qquad (2)$$

where ω is circular frequency of the field, ν_e is frequency of transport collision of electrons with molecules of air, e and m are electron charge and mass respectively. Under condition $\nu_e \gg \omega$, that at wave frequency of 37 GHz in normal density air is satisfied, the expression (2) takes the following form

$$w_e = \frac{e^2 E^2}{2m\nu_e}. \qquad (3)$$

In spark discharges in dense gases and, particularly, in the atmosphere the streamers usually develop simultaneously in large amount. For instance, in the streamer zone of the leader with volume of about cubic meter $10^5 - 10^6$ streamers present simultaneously [1]. Power W_a of microwave radiation absorption per single area of the cross section of the beam, passing through the section, occupied with streamers, of characteristic size, much bigger than the microwave beam radius, under condition of the microwave beam cylindricity (field amplitude consistency along the beam axis), is equal

$$W_a = \frac{e^2 E^2}{2m\nu_e} n_{es}, \quad n_{es} = \int n_e dz, \qquad (4)$$

where n_{es} is integral of electrons concentration along the microwave beam axis. Relative attenuation of the microwave radiation, passing through the section, occupied with the streamers, is equal to ratio of specific (per the beam area unit) power, absorbed in streamers, and density of power flow in the incident microwave beam $S_0 = 0.5\sqrt{\varepsilon_0/\mu_0}E^2$:

$$\delta = \frac{W_a}{S_0} = \frac{e^2 n_{es}}{m\nu_e}\sqrt{\frac{\mu_0}{\varepsilon_0}}. \qquad (5)$$

Equation (5) gives the relation of value of n_{es} and the measured value of the probing microwave radiation attenuation δ:

$$n_{es} = 2.8 \cdot 10^{13} \delta\,\mathrm{cm}^{-2}. \qquad (6)$$

Streamer discharges, usually consisting of multiple simultaneously moving streamers, appearing at various stages of spark discharges development or developing independently, and being part of the general discharge process, often consist of almost equal streamers. For instance, the streamer zones of the leaders in the phase of the leader free movement and in the beginning of the breakthrough phase possesses such property [21]. In this case the value n_{es} can be presented the following way:

$$n_{es} = N_e \int n_{str} dz, \qquad (7)$$

where N_e is full number of free electrons in a single streamer, and n_{str} is streamers concentration in the space. If concentration of streamers n_{str} and its distribution in the space can be observed from independent measurements, then using the measurement of relative attenuation of the microwave radiation δ it is possible, using (6) and (7), to get the full number of electrons in a single streamer N_e (as it was done in [21]). Let's evaluate the value δ in the case, when the whole cloud (cloud size along the microwave beam is $L \sim 1\,\mathrm{m}$) is filled with streamers, having the same parameters and concentration as streamers in the streamer zone of the positive leader [21]: $N_e = 3 \cdot 10^{10}$, $n_{str} = 0.1\,\mathrm{cm}^{-3}$. Then we get

$$n_{es} \sim 3 \cdot 10^{11}\,\mathrm{cm}^{-2}, \quad \delta \sim 0.01. \qquad (8)$$

2.2. Microwave radiation scattering with long spark channels

Conductivity of the leader channels exceeds the conductivity of the streamer channels by an order of four [1]. Interaction of electromagnetic wave with such channels is similar to diffraction on a perfectly conducting cylinder. In this case, the absorption of microwave radiation in plasma of such channels is low, while attenuation of the passing radiation is caused by scattering on channels. From the solution of the problem of diffraction of flat monochromatic electromagnetic wave on infinite round perfectly conducting cylinder [24] it is followed, that the amplitude of the electric field E_r in the reflected cylindrical wave is equal to

$$E_r = E_0\left[\frac{J_0(ka)}{H_0^{(2)}(ka)}H_0^{(2)}(kr) + 2\sum_{m=1}^{\infty}\frac{J_m(ka)}{H_m^{(2)}(ka)}H_m^{(2)}(kr)\cos(m\varphi)\right], \quad (9)$$

where E_0 is amplitude of incident flat wave, a is cylinder radius, k is wave number of incident wave, J_m is Bessel function, $H_m^{(2)}$ is Hankel function of the second kind, r and φ are cylindrical coordinates. The effective radius of scattering d_{eff}, equal to ratio of the scattered power per length unit of the cylinder W_r and flow density in the incident wave S_i, is equal to

$$d_{\text{eff}} = \frac{W_r}{S_i} = \frac{1}{|E_i|^2}\int_0^{2\pi}|E_r|^2 r d\varphi\Big|_{r\to\infty} = \frac{4}{k}\left\{\left|\frac{J_0(ka)}{H_0^{(2)}(ka)}\right|^2 + 2\sum_{m=1}^{\infty}\left|\frac{J_m(ka)}{H_m^{(2)}(ka)}\right|^2\right\}. \quad (10)$$

Figure 2 shows the dependence of the ratio of the effective scattering diameter and the cylinder diameter on the ratio of the cylinder diameter and the electromagnetic wave length, obtained from formula (10).

From (10) it is easy to get the part δ of the power of the monochromatic Gaussian beam of the electromagnetic waves with radius R and wave number k, scattered on the conducting cylinder with radius $a \ll R$, located perpendicular to the beam axis at a distance b from it:

$$\delta = \frac{4}{\sqrt{\pi}kR}e^{-\frac{b^2}{R^2}}\left\{\left|\frac{J_0(ka)}{H_0^{(2)}(ka)}\right|^2 + 2\sum_{m=1}^{\infty}\left|\frac{J_m(ka)}{H_m^{(2)}(ka)}\right|^2\right\}. \quad (11)$$

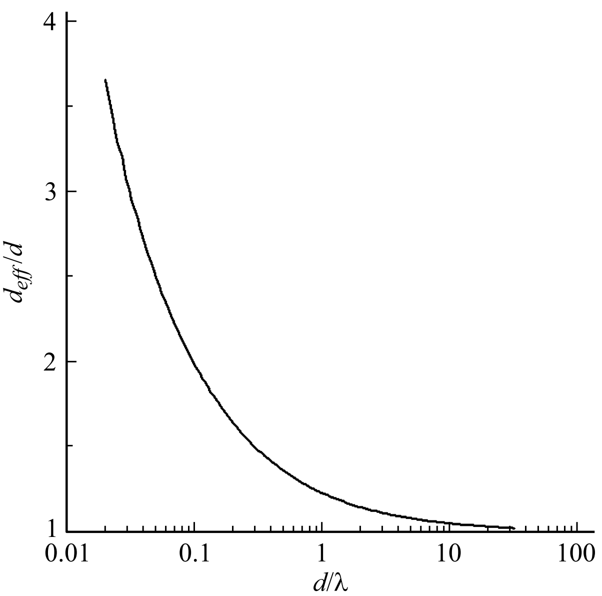

Figure 2. Ratio of the effective scattering diameter and diameter of perfectly conducting cylinder versus ratio of the cylinder diameter and wave length.

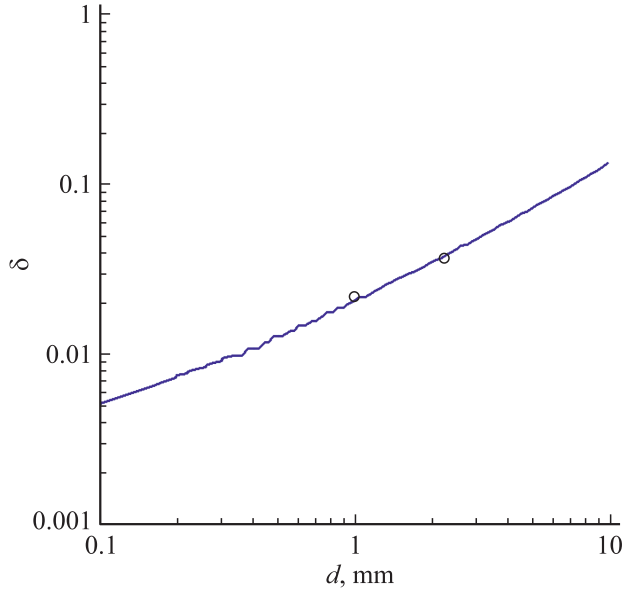

Figure 3. Relative attenuation of the microwave radiation with frequency of 37 GHz in the beam with radius $R = 5$ cm at diffraction on the conducting cylinder with diameter d, located on the microwave beam axis and oriented along direction of beam polarization, depending on the cylinder diameter. Circles — experiment with metal cylinders.

Figure 3 shows the dependence of the relative attenuation δ of a beam of electromagnetic waves with the radius of 5 cm and frequency of 37 GHz on the cylinder diameter at cylinder location on the beam axis ($b = 0$), calculated by the formula (11). Circles in Fig. 3 indicate the results of the test measurements of the relative attenuation at putting the metal wires with diameter of 1 and 2.25 mm to the waist of the microwave beam.

3. Some results of the measurement of the microwave radiation attenuation in artificial cloud during intracloud discharges

Two characteristic signal types were observed in the relative attenuation of the microwave radiation during electric discharges in the cloud. One of them are intensive short peaks, amplitude of which was usually several percents (the most intensive — up to 10%), while duration was 0.3–0.4 μs. Another form of the relative attenuation are the smooth humps, amplitude of which was about 1% and less, while duration was several dozens of microseconds. In the beginning of the smooth humps there was always an intensive peak, while the peaks could appear alone.

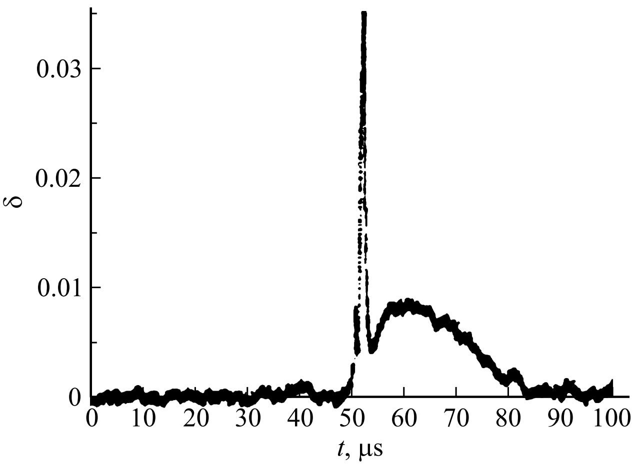

Figure 4. Relative attenuation δ of the microwave radiation, passing through the electrified cloud, during electric discharges passage inside the cloud (adapted from [25]).

Figure 4 shows the recording of the relative attenuation of the microwave radiation, where both forms are present [25]. Studies of the intracloud discharges [26], performed using microwave diagnostics along with recording with IR camera and electric measurements, have showed, that sharp peaks of the probing microwave radiation attenuation were caused by streamer flashes, developed in the cloud. Smooth humps are probably related to the streamer zones of the leaders, that in our experiments were usually initiated on the grounded plane and moved towards the cloud. Value of absorption sometimes exceeded the evaluation (8), made above for parameters of the streamer zone of the positive leader. It means that the streamer discharges in the electrified cloud can be more intensive, i.e. have higher concentration of streamers or concentration of electrons in streamers, than the streamer zones of the leaders of the positive long sparks.

Conclusion

Microwave diagnostics is an efficient tool for studying the electric discharges in the cloud environment, that allows to get information on parameters of intra-cloud discharges, unavailable to traditional optical methods, that are usually used in long spark experiments.

The observed results can be useful for studying the microwave radiation propagation through the atmosphere regions with lightning activity for evaluation of intensity of the microwave radiation absorption and scattering with discharges inside thunderclouds.

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Conflict of interest

The authors declare that they have no conflict of interest.

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