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Possible mechanism of ice blooming in the microwave range near 0°C

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An explanation of the effect of the blooming of fresh ice in the microwave range at 0°C is proposed. Blooming is associated with the occurrence of plasmon resonance in the islet films of the medium that occur during the plastic flow of ice under the influence of temperature deformations near the phase transition.

Keywords: fresh ice, microwave attenuation, plastic deformation, plasmon resonance.

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The dielectric characteristics of fresh ice in the microwave range are quite well studied. An area approximately from -0.5 to 0°C remains unexplored. At the same time, it is implicitly assumed that some areas of ice melt on the crystal faces, in the pore space near the temperature of the phase transition, where water-soluble impurities and pollution particles accumulate, which results, for example, in the complexity of interpretation of remote sensing data [1].

It was reported in [2,3], that „bleaching" of fresh ice near its melting temperature in the microwave range at frequencies of 3.3, 5.2, 34 and 90 GHz. This observation contradicts the assumption of an increase of electromagnetic losses because of melting of some areas of the object under study near the phase transition point. An explanation of the effect associated with shear plastic deformation of ice crystals along the basic planes was put forward, since the bleaching was observed if the vector of the electric field of the waves was in this plane [3]. Since the existence of a negative differential viscosity of ice was known [4], the bleaching was associated with this feature, in which a thin layer of water molecules is in an unstable state. However, a more detailed explanation of the phenomenon was not given.

New experiments were performed in this study to measure the real (ε') and imaginary (ε'') parts of the relative permittivity of ice using a resonator near the frequency of 3.5GHz. A rectangular resonator of H_{101} type with internal dimensions of $58 \times 26 \times 25$ mm is used. In addition, some other experimental and theoretical studies on the structure of water were generalized, which allowed putting forward a clarifying mechanism of the phenomenon to explain the abnormal manifestations of the electromagnetic properties of fresh ice in the microwave range [5].

Figure 1 shows a diagram of an experiment to study a resonator with a fresh ice. The transmission characteristics of the resonator were measured in the experiment: the transmission power at the resonant frequency (P), the bandwidth, and the sample temperature (T). The ice sample was cut from the ice cover of a freshwater lake in the central area in height, where the optical axes of the crystals were predominantly oriented vertically according to measurements. A sawn sample with dimensions corresponding to the dimensions of the cavity of the resonator was placed in its volume in such a way that the basic planes of the crystals were parallel to the electric field vector. The lower resonant frequency of the resonator is 6.182GHz. The mineralization of the ice was 5 mg/kg. The measurements were started at a resonator temperature from -5 to -10°C with its heating in a laboratory room at an air temperature of $\sim 20^\circ$C. The thermocouple was placed in the resonator housing. The accuracy of the relative temperature measurements was on the order of 0.1°C. Measurement rate is one count per 3 s.

The results of one of the experiments are shown in Fig. 2. In principle, they replicated the previous results. Their peculiar feature in case of measurements at a frequency of 3.5GHz was that the power increment ΔP because of approaching 0°C turned out to be more than 2 times higher than the initial value P at the point marked with an arrow in Fig. 2. ΔP was $10-20\%$ in previous experiments [2,3]. Calculations of the value of ε'' ice (taking into account losses in an empty resonator) showed that this value decreased by 4 times at the maximum transmission of the

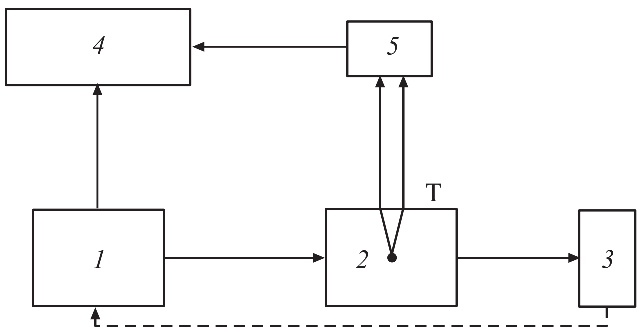

Figure 1. A diagram of a setup for measuring the dielectric characteristics of ice near the phase transition temperature. *1* — the frequency response meter P2M-18/2 („Micran"), *2* — the resonator with thermocouple (T), *3* — the meter detector, *4* — the information acquisition and recording system, *5* — the thermocouple amplifier.

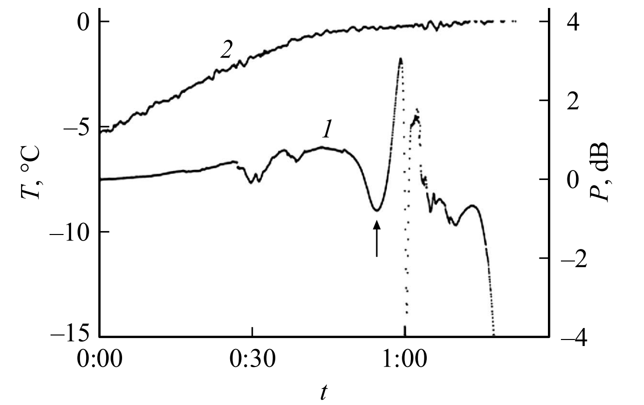

Figure 2. The results of measurement of transmittance power of the resonator with ice relative to a reference level of 0 dB (*1*) and temperature (*2*) depending on the heating time. The arrow marks the beginning of bleaching.

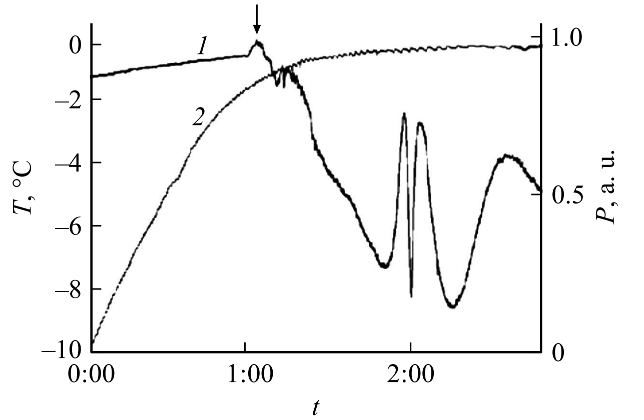

Figure 3. The dependences of the power of radiation passing through the ice sample at a frequency of 32 GHz (*1*) and temperature (*2*) on the heating time [6]. The arrow marks bleaching.

resonator and approached the value of $5 \cdot 10^{-3}$ (with a measurement error of $0.5 \cdot 10^{-3}$). What turned out to be unusual was that about a sharp 5-fold drop of the power of the signal passing through the resonator with the sample was observed near the peak of P.

A similar behavior of the power of the radiation passing through the sample was detected earlier in [6] when the ice block was exposed to the radiation (Fig. 3). A sharp increase of absorption against the background of a peak of P was not observed in all experiments. However, its consideration made it possible to clarify the physical mechanism of the observed bleaching of the medium.

The analysis of literature sources shows that the signal intensity during spectrometric measurements of composite media can significantly increase due to plasmon-polariton excitations at the boundary of conductive and dielectric media [7,8]. The scattering and absorption resonances occur in the case of the formation of conductive nanoscale particles in a weakly absorbing medium, as well as an increase of the power of signals propagating along chains of such particles. A sharp decrease of radiation at certain frequencies, known as plasmon resonance „quenching" may occur when they interact with the medium.

However, fresh ice is a chemically homogeneous medium (with a small amount of impurities $\sim 10^{-5}$). At the same time, the bleaching effect occurred when the ice was heated when approaching 0°C before melting as it was found in [2,3]. Melting was determined by the occurrence of attenuation in the medium and the achievement of an ice temperature close to 0°C, with the measurement accuracy of ~ 0.1°C. As noted above, a sharp decrease of attenuation before its subsequent rather rapid increase was unusual.

Therefore, a new hypothesis was put forward that plasmon polaritons are generated in the medium when plastic flow occurs in the studied samples along the basic planes of ice crystals as a result of deformations caused by a temperature gradient. The effect was explained in [2,3] by the flow of ice crystals along the basic planes, but a description of the amplification mechanism was not proposed. If we also accept the assumption of the formation of nanometer-sized islands at the boundaries of the layers along which plasmon polaritons slide and appear, then it is necessary to understand the mechanism of a significant increase of conductivity in them. The following explanation is possible. Liquid water films are formed in the layers through which sliding occurs when hydrogen bonds are broken. It was shown in [9] that ferroelectric ordering of water dipoles occurs at the flat boundary of liquid water with a dielectric in the case of a hydrophobic (or partially hydrophobic) surface. At the same time, a layer with high electrical conductivity is formed in the contact layer between the ferroelectric and the dielectric as it was theoretically and experimentally found in [10]. It can be six orders of magnitude higher than the conductivity of a bulk material. This effect is determined by the difference in the values of the static permittivity of the two materials. Moreover, the plastic deformation is known not to occur in the form of a smooth flow, but manifests itself in the form of autowaves of localized plasticity [11]. The wavelengths of these waves in the medium are in the range of 0.5–2 cm. These waves are also associated with the manifestation of charge separation because of the acousto-electric effect [12]. As a result, the flow through the films constitutes a freezing-melting of ultrathin layers of ice with the formation of conductive regions and electrical potentials. The insular conducting two-dimensional formations occur in the volume of the ice body and plasmon polaritons appear during the process of change of the state of ice in local areas of crystals with the occurrence and disappearance of flow waves. Their resonant frequencies are determined by the size, conductivity of the layers and characteristics of the contact media. At the same time, it can be expected that the resonant properties of the islands have a wide spectrum and reach the frequencies of the microwave range [7,13]. The quenching of the plasmon amplification of the field can be determined by the existence of a certain ambient state of conductive inclusions in the medium from impurities in the form of liquid and solid salt inclusions, some of which are always present in fresh water.

It should be noted that both bulk and bound water may appear in the ice near 0°C, when the melting process occurs. The bound water has transitional values of ε' and ε'' between ice and bulk water according to existing concepts. Therefore, the appearance of bound water in any case should result in an increase of electromagnetic losses and a decrease of the resonant frequency of the resonator. Therefore, its formation cannot result in the effect of ice bleaching. The observed phenomena occurred in our experiments before the appearance of noticeable amounts of both bulk and bound water, which followed from the absence of a pronounced shift in the resonant frequency of the resonator.

The effect of decrease of the loss factor to a value close to zero in the microwave range was observed earlier, for example in [14] at a wavelength of 8.2 mm. The measured linear attenuation in the samples varied from 0 to 13 dB/m, although for chemically pure ice it is calculated to be 2 dB/m. The attention was paid to these data in a number of publications, but the effect was not explained. The knowledge of the physical mechanism of ice bleaching at 0°C is of interest for the study of electrical phenomena in cryospheric formations.

Thus, the bleaching of fresh ice formation in the microwave range, as well as the peculiarities of its change as it approaches the point of phase transition, can be explained by the appearance of plasmon polaritons when waves of plastic flow occur along films parallel to the basal planes of crystals. The flow occurs in the form of autowaves of localized plasticity, which results in the formation of regions with alternating crystal structure and active regions in quasi-liquid films of the medium. The nanoscale island films are formed in these films during melting and freezing of thin layers of water.

The plasmon resonances occur in the island films because of the occurrence of metallic conductivity caused by ferroelectric ordering at the contact of ice and quasi-liquid layers through which flow occurs. Their geometric factors determine the width of the resonance band, extending to zero frequencies in the case of anisotropy of the shape of the islands. A sharp increase of attenuation („quenching" of plasmon resonance) is observed in some cases because of the impact of impurities in the volume of the medium at contact with the islands.

The effect of bleaching and its accompanying features can be observed before melting in a variety of natural frozen structures (for example, in frozen soils, glaciers, ice and snow covers), since they contain a significant number of small solid inclusions and chemical compounds trapped in the frozen environment in addition to ice crystals, and therefore there is a wide range of resonant frequencies.

Conflict of interest

The author declares that he has no conflict of interest.

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