DETERMINATION OF THE COMPLEX DIELECTRIC PERMITTIVITY OF ICE IN THE MILLIMETER-WAVE RANGE BY THE RESONATOR METHOD

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A resonator method for the determination of the complex dielectric permittivity of ice in the 8-mm wavelength range has been proposed. For this purpose, a dielectric resonator was fabricated of the material under investigation, and it was excited at whispering gallery (WG) waves. The electrodynamic characteristics of resonators that had been made by freezing water of various types have been measured experimentally. This allowed the corresponding values of the real and imaginary parts of the dielectric permittivity to be calculated.

1. Introduction

The electric characteristics of ice and snow at extremely high frequencies (EHFs) attract the attention of researchers since the period of formation of radar engineering [1–3]. In recent years, owing to the development of radio communication, radioastronomy, and the remote sounding methods of Earth's mantle and atmosphere in the millimeter-wavelength range of the electromagnetic spectrum, the interest to the determination of ice characteristics became even stronger [4–6]. In order to develop models for snow and clouds, reliable values for the complex dielectric constant of ice and its dependences on the frequency and temperature are needed. Until the present time, the techniques of measurements in a free space or in wave-guides have been used to study the dielectric characteristics of ice and snow in the EHF-range. The corresponding results concerning the complex dielectric permittivity of ice that were published in numerous available publications differ considerably. Especially large divergences are observed for measurements of the imaginary part of dielectric permittivity in the millimeter-wave range, which is associated, first of all, with its low value, as well as with its strong dependence on the temperature [7–9]. Unfortunately, the resonator methods for the determination of the complex dielectric permittivity in the millimeter-wave range in bulk specimens of the substance, which could increase the accuracy of dielectric permittivity measurements, have not been used until now. Widely known metallic bulk resonators would be too tiny for this range, whereas the application of quasioptic resonators with metallic mirrors allows measuring the electric characteristics of materials fabricated in the form of thin plates or films only.

In order to determine the dielectric characteristics of insulators with low losses of electromagnetic energy in the EHF-range, the methods based on fabricating the dielectric resonators (DRs) that are excited at waves of the WG type are widely used nowadays [10, 11]. Ice is an insulator; the imaginary part of its dielectric permittivity can be three to four orders of magnitude lower than the imaginary part of the dielectric permittivity of water. In our opinion, this gives an opportunity to fabricate an icy DR with a high quality factor and to determine, by measuring its characteristics, the dielectric properties of ice, which it has been made up of. In this case, there is no necessity in using complicated interferometric schemes with two measurement channels, two generators, two resonators, and so on. This work aimed at both fabricating a hemispherical DR from ice which is excited at WG waves and studying its electrodynamic characteristics.

Along with disk-shaped DRs excited at WG waves, hemispherical DRs have been proposed and have become

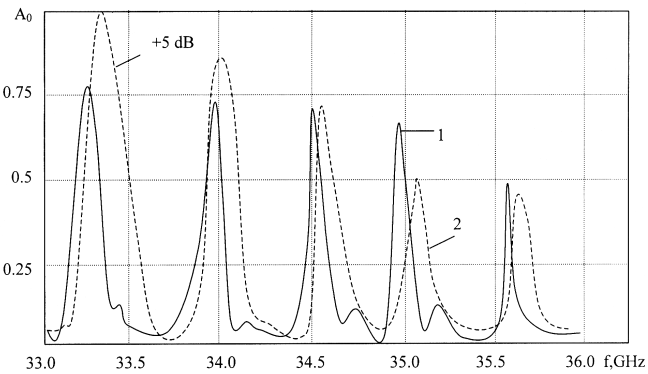

Fig. 1. Spectra of EHF-oscillations in hemispherical dielectric resonators made from ice. The ice was made from distilled (*1*) and tap (*2*) water

widely spread recently [12,13]. In comparison with disk-shaped DRs, such resonators have a Q-factor that is by 20–25% higher owing to the reduction of radiation losses. The calculation of the electrodynamic parameters of such resonators can be carried out with a less number of approximations and assumptions; therefore, it is more exact. Moreover, a hemisphere fabricated from ice is more resistant to the destruction of its fragile edge.

2. Experimental Part

In experiments, hemispheres made up from ice, which was artificially prepared from distilled or tap (boiled and unboiled) water, as well as from melted snow taken in the city's streets. Water was poured into a mould, which had the shape of a metal bowl and whose internal polished surface was a hemisphere. To diminish the air content in the specimen, water was preliminarily heated up to 50–60 °C. Then, the mould was placed into a freezing chamber, and water was gradually frozen for several hours. The minimal temperature in a refrigerator reached −15 °C. An ice specimen was extracted from the mould in a cool room and was installed on a measuring setup. The air that still remained in the ice, became accumulated near the hemisphere's pole and formed an opaque muddy ice structure. In the vicinity of the equatorial plane, ice was more homogeneous and transparent. Therefore, for studying WG waves, the E_{n11} oscillation type was selected, which was excited by a wave that propagated in a narrow layer along the equatorial plane. It should be noted that the propagation of an electromagnetic WG wave near the equatorial plane in a thin ice layer does not require that a specimen prepared for measurements should be of high quality in the other part of the hemisphere. The central part of the hemisphere may even contain water in the liquid state. In this regard, our technique for measuring the dielectric permittivity differs from the others, which lay down more rigorous conditions with respect to the homogeneity of the specimen over its whole volume. The ice temperature of −15 °C could be kept constant for several minutes, the period of carrying out measurements of the electrodynamic properties of a hemispherical DR made up from ice. The appearance of a water film on the spherical surface resulted in a fast reduction of the resonator Q-factor, down to a complete loss of its resonator properties. We also experimented with DRs fabricated by freezing water down to a temperature of −17 °C.

The tested hemispherical ice resonators 84 mm in diameter were excited at five resonant oscillations of the E-type ranging from 33 to 37 GHz. The waves emitted by a dielectric wave-guide were used for excitation, making use of their distributed coupling with WG waves in the resonator. The dielectric wave-guide with a transverse cross-section of 7.2×3.4 mm^2 was installed near and in parallel to the equatorial plane of the hemisphere. Resonance fields became concentrated in the 12-mm equatorial layer, where the ice structure was homogeneous. For the reception of the signal, a similar dielectric wave-guide, which was located on the opposite side of the hemisphere, was used. If the dielectric wave-guide was installed near the hemisphere's pole, the polar layer of electromagnetic fields turned out violated, which evidenced for a poor quality of ice near the pole. Ice inhomogeneities in this region were observed visually as well. The features of the hemisphere's resonance frequencies were studied with the help of a panoramic meter of the voltage standing-wave ratio. It was used to determine the resonance frequencies f_n and the corresponding Q-factors of the resonator.

3. Discussion of Experimental Results

Figure 1 demonstrates the dependences of the amplitude A of the EHF-signal transmission through the resonator at the frequency f_n in the range 33–37 GHz measured for two resonator hemispheres fabricated from distilled (curve *1*) and unboiled tap (curve *2*) water. Five experimentally observed resonances are located almost equidistantly along the frequency axis with an interval $\Delta f_n = 0.685$ GHz for the ice made from distilled water and $\Delta f_n = 0.75$ GHz for the ice from unboiled tap water. Those frequency intervals are determined by the hemisphere's diameter and the real part of the complex dielectric permittivity of the material, which it is made of. The Q-factor of the resonant curve is governed by dielectric losses in the substance of the resonator and allows the imaginary part of the complex dielectric permittivity of the material, which the resonator is fabricated from, to be calculated. The quality factor of the resonators made up of distilled water was $Q_1 = 1420$, and that of resonators made up of tap water $Q_2 = 320$. Those values slightly depend on the operation frequency selected within the frequency range under investigation. The reason is that, under experimental conditions, only modes with large WG index ($n > 40$) are excited in the resonator, so that their radiation energy losses are almost constant. Making use of the relations taken from work [14] and applying the experimental values for frequency intervals Δf_n and Q-factors, the values of the complex dielectric permittivity were calculated. According to the experimental results which are listed in Table, the calculated values of the real and imaginary parts of the dielectric permittivity of ice fabricated from distilled water are $\varepsilon' = 3.13 \div 3.14$ and $\varepsilon'' = 2.26 \times 10^{-3}$, respectively, while for ice made from unboiled tap water $\varepsilon' = 2.58 \div 2.67$ and $\varepsilon'' = (8.6 \div 8.9) \times 10^{-3}$, respectively. These data are of interest as the limiting cases for dielectric characteristics of ice, because the values of the real and imaginary parts of the dielectric permittivity of ice made from either boiled tap water or melted snow lie between them. It is also interesting that the imaginary part of the dielectric permittivity of ice from melted snow is close to that for ice from distilled water, which evidences for low energy losses of waves in the given medium.

Besides a noticeable discrepancy between the quality factors of oscillation for those two ice resonance hemispheres (from distilled and tap water), less evident deviations between the measured characteristics of resonators, reproduced from experiment to experiment, were observed. Such deviations originated from the quality of fabricated ice: the availability of tiny air bubbles in it and the manifestations of a polycrystalline structure or fine cracks.

Also of interest is the issue concerning the stability of electrodynamic properties of ice, subjected to a high (room) temperature of the environment. For this purpose, the measurements of the resonance response amplitude on the heating time were made for ice,

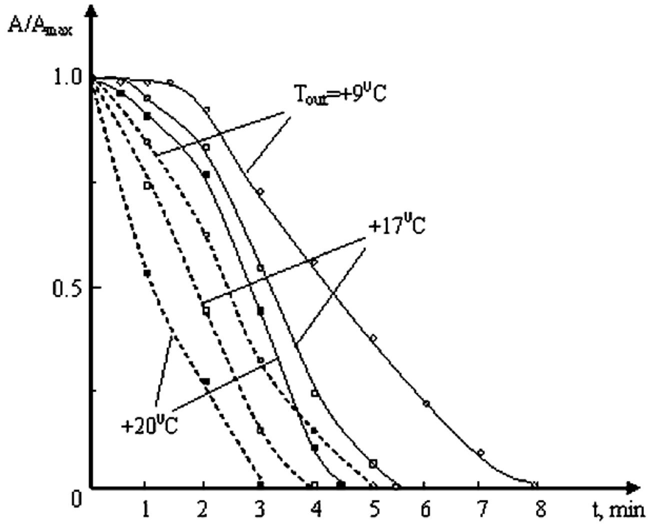

Fig. 2. Dependences of the resonance response amplitude of ice hemisphere oscillations on the heating time for various heating temperatures (see the explanation in the text)

provided that the environment temperature was +9, +17, or +20 °C. The results obtained are plotted as the dependences of the resonance response amplitude A normalized by its maximal value $A_{\max}$ on the dwell time t, for which ice was subjected to a positive (on the centigrade scale) temperature of the environment (Fig. 2). After measurements having been carried out (the time of one measurement was about 5 min), the ice resonator was frozen again to the initial temperature. The time of such repeated freezing varied from 2 to 24 hours. In Fig. 2, the solid curves correspond to the data obtained after the repeated freezing for 24 h, and the dotted ones correspond to the repeated freezing for 2 h.

Figure 2 testifies that the rate of attenuation of a WG wave in ice grows if the environment temperature increases. At lower environment temperatures (+9 °C), ice can preserve its electrodynamic properties during some time (up to 1.5 min), which is confirmed by a constant amplitude of the observed resonance response. In this case, the period of "ice restoration" – the time of repeated freezing – is important, because, as the figure shows, in the case where the time of repeated freezing was short (2 h), the variation of the ratio $A/A_{\max}$ was observed proceeding from the first seconds of

Water type	Δf, MHz	Q_0	ε'	ε''	T, °C	f, GHz
Distilled	0.682 – 0.684	1410 – 1420	3.13 – 3.14	2.26×10^{-3}	−15	32 – 37
Boiled tap	0.689 – 0.692	418 – 426	3.08 – 3.09	7.7×10^{-3}	−15	32 – 37
Unboiled tap	0.740 – 0.750	311 – 320	2.58 – 2.67	$(8.6\div8.9)\times10^{-3}$	−15	32 – 37
Melted snow	0.722 – 0.724	1390 – 1400	2.79 – 2.80	2.07×10^{-3}	−15	32 – 37

the measurement. It is obviously associated with the heat capacity of ice. Being refrozen for a long time, ice can compensate the influence of positive temperatures of the environment at the first stages of the measurement by mobilizing its own resources.

4. Conclusions

Thus, the fulfilled researches have proved the possibility to create high-quality quasioptic resonators from ice which are excited in the millimeter-wave range (oscillations of the WG type). It has been shown that such resonators can serve as high-sensitive cells for measuring the complex dielectric permittivity of ice, which they are made from. The further researches demand that the quality control over the fabrication of hemispherical specimens from ice be enhanced in order to reduce the spread of measured dielectric characteristics from experiment to experiment.

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РЕЗОНАТОРНИЙ
МЕТОД ВИЗНАЧЕННЯ КОМПЛЕКСНОЇ
ДІЕЛЕКТРИЧНОЇ ПРОНИКНОСТІ ЛЬОДУ
У МІЛІМЕТРОВОМУ ДІАПАЗОНІ ДОВЖИН ХВИЛЬ

О.Я. Кириченко, О.Є. Когут, В.В. Кутузов, В.А. Солодовник

Р е з ю м е

Запропоновано резонаторний метод визначення комплексної діелектричної проникності льоду у 8-мм діапазоні довжин хвиль. Для цього виготовляють з досліджуваного матеріалу діелектричний резонатор, що збуджується на хвилях шепочучої галереї. Експериментально отримані електродинамічні характеристики резонаторів, виготовлених шляхом заморожування різних типів води, дозволили розрахувати відповідні їм значення дійсної та уявної частин діелектричної проникності.