Dielectric properties of marsh vegetation

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ABSTRACT

The present work is devoted to the measurement of the dielectric properties of mosses and lichens in the frequency range from 500 MHz to 18 GHz. Subjects of this research were three species of march vegetation – moss (*Dicranum polysetum Michx*), groundcedar (*Diphasiastrum complanatum (L.) Holub*) and lichen (*Cladonia stellaris*). Samples of vegetation were collected in Tomsk region, Western Siberia, Russia. Complex dielectric permittivity was measured in coaxial section by Agilent Technologies vector network analyzer E8363B. Green samples was measured for some moisture contents from 100% to 3–5 % during a natural drying. The measurements were performed at room temperature, which remained within 21 ÷ 23 ° C.

The frequency dependence of the dielectric constant for the three species of marsh vegetation differ markedly. Different parts of the complex permittivity dependency on moisture were fitted by line for all frequency points. Two break point were observed corresponding to the transition of water in the vegetation in various phase states. The complex permittivity spectra of water in the vegetation allow determining the most likely corresponding dielectric model of water in the vegetation by the method of hypothesis testing. It is the Debye’s model. Parameters of Debye’s model were obtained by numerical methods for all of three states of water. This enables to calculate the dielectric constant of water at any frequency range from 500 MHz to 18 GHz and to find the parameters of the dielectric model of the vegetation.

Keywords: dielectric properties, permittivity, remote sensing, vegetation, marsh

1. INTRODUCTION

Changing climate and the exchange of carbon in the atmosphere are the subject of attention of scientists for many years. Ecosystems of forest and marsh complexes, particularly in Western Siberia, are a natural indicator of these processes. A study of the current state, mechanisms of their functioning and dynamics is an actual problem. The transformation of biota and subarctic landscapes, state of permafrost as a result of climate change in the current conditions and retrospective represent particular interest in the investigations. When continuous observations are conducted using remote sensing technology the issue of data recovery algorithms and dielectric models of investigated surface move into first place [1, 2]. It is necessary to take into account the vegetation cover for a more accurate interpretation of the data.

This task requires a detailed study of various types of vegetation, their dielectric properties and influencing factors for the dielectric constant such as a moisture, temperature and frequency of electromagnetic waves. For example, B.L. Shrestha and H.C. Wood [3] presented the results of the dielectric properties of alfalfa in a wide range of temperatures, moisture, pressure and frequency. Mosses, lichens and groundcedares are widespread in the subarctic zone ecosystems. These marsh species are matter of topical interest for the Siberian region along with the plants of agriculture and forest.

The present work is devoted to the measurement of the dielectric properties of mosses and lichens in the frequency range from 500 MHz to 18 GHz. Spectroscopic microwave dielectric model of wet soils that was introduced by V.L. Mironov [4, 5] is well proven in the SMOS retrieval algorithm [6]. The similar approach was applied in this work for marsh vegetation.

2. MATERIALS AND METHODS

Subjects of this research were three species of march vegetation – moss (*Dicranum polysetum Michx*), groundcedar (*Diphasiastrum complanatum (L.) Holub*) and lichen (*Cladonia stellaris*). Samples of vegetation were collected in Tomsk region, Western Siberia, Russia. Green samples were measured for some moisture contents from 100% to 3–5 % during a natural drying. The measurements were performed at room temperature, which remained within 21 ÷ 23 ° C.

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Weight moisture of samples was measured and defined as the ratio of the mass of water in the sample to the mass of the dry sample. Sample preparation was carried out by light grinding them to place it in the coaxial cell. Moisture was determined by the formula: $W = (m_{\text{wet}} - m_{\text{dry}}) / m_{\text{dry}}$, where m_{wet} and m_{dry} – mass of wet and dry samples, respectively. Some samples of the measured moisture of more than a hundred percent, it is because the mass of water in the sample is greater than the mass of the dry sample.

We applied mmeasurement method by a coaxial cell that has been used successfully to measure the dielectric properties of soils [7, 8] and liquids [9] at the frequency range of 100 MHz to 18 GHz.

The components of the scattering matrix of coaxial measuring cell – complex reflection coefficients (parameters S11, S22) and transmission coefficient (parameters S12, S21) – were measured using a vector network analyzer PNA E8363B production of Agilent Technologies. Measuring scheme is shown in Figure 1 (a). We used a coaxial section with different lengths (17 mm, 37 mm and 57 mm) for samples of different moisture.

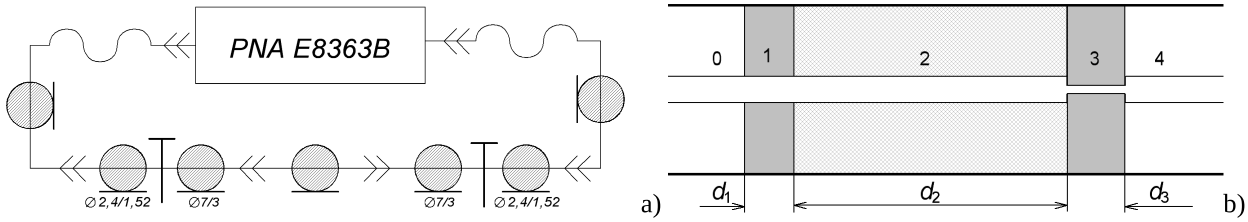

Figure 1. Scheme of the measurement setup (a) and location of the sample in the coaxial cell (b): 0, 4 – air environment; 1, 3 – Teflon collars, 2 – the sample.

Coaxial cell is a layered structure; its diagram is shown in Figure 1 (b). A sample of plants is placed in a cell between two Teflon (PTFE) collars 1 and 3. Teflon ppermittivity is $\varepsilon_f=2.05\pm0.05 - j\cdot 6\cdot 10^{-4}$ and air permittivity $\varepsilon=1 - j\cdot 0$, j means imaginary unit.

The characteristic impedance of section 0 and 4 was obtained as impedance of empty coaxial line and is equal to $Z_0 = Z_4 = 49.65 - j \cdot 0$ Ohm. The characteristic impedance of section 1 and 3 was calculated as the $Z_0 / \sqrt{\varepsilon_f}$ and equals $Z_1 = 34.67 - j \cdot 0.005$ and $Z_3 = 51.79 - j \cdot 0.007$ ohms. A line conditioning was found to be satisfactory. The characteristic impedance of section 1 is equal $Z_0 / \sqrt{\varepsilon_x}$, here ε_x – complex permittivity of the sample.

The calculation of the dielectric constant was carried out by the scattering matrix parameters of a four-pole network. The complex reflection coefficient (parameter S_{11} and S_{22}) and the complex transmission coefficient (parameter S_{12} and S_{21}) for the layered structure can be determined according to [10] as follows:

$$S_{12} = \prod_{i=1}^{n} \frac{Z_{in}^{(i)} + Z_i}{Z_{in}^{(i)} + Z_{i+1}} e^{j\phi_i}, S_{11} = \frac{Z_{in}^{(1)} - Z_0}{Z_{in}^{(1)} + Z_0}. \tag{1}$$

Input impedance Z_{in} for each section with index $i = 1, 2, 3$ is calculated as follows:

$$Z_{in}^{(i)} = \frac{Z_{in}^{(i+1)} + Z_i th(jk_i d_i)}{Z^{(i)} + Z_{in}^{(i+1)} th(jk_i d_i)} Z^{(i)}. \tag{2}$$

Here $k_i = k_0 \sqrt{\varepsilon_i}$ is complex wave number of i-th section, where ε_i – complex dielectric constant of i-th section, $k_0 = 2\pi f / c$ is the wave number in vacuum (f – frequency, c – velocity of light). The complex dielectric constant as unknown value was found as the solution of the inverse problem by secant method.

Figure 2 shows the experimental (points) and calculated (line) values of the transmission coefficient (scattering matrix component S_{12} and S_{21}) of the coaxial cell length of 57 mm with moss sample. This method allows distinguishing confidently between samples with different moisture.

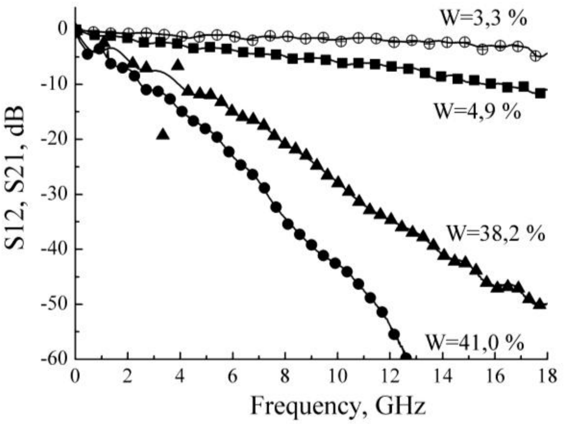

Figure 2. Electromagnetic response of the sample of groundcedar measured in cell with length 57 mm.

3. DATA

The figure 3 shows the results of measurements of the frequency dependence of the complex dielectric constant of marsh vegetation for some species. We can see values of permittivity for different species of vegetation with the same moisture differ markedly. Dielectric constant is integral characteristic of matter and depends on many factors, but it enables to identify species of plants.

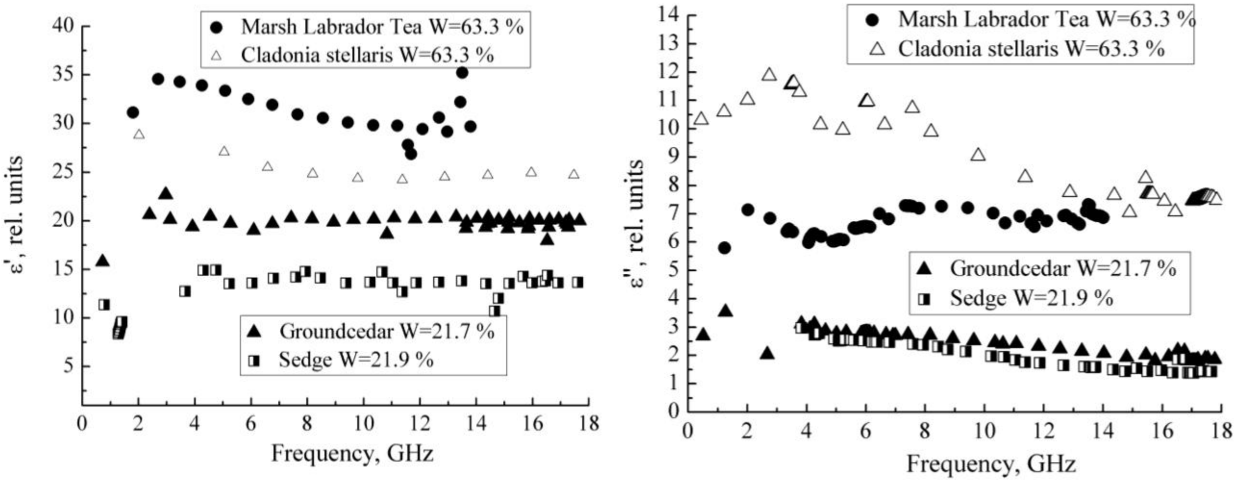

Figure 3. Complex permittivity of different species of plants at the same moisture.

Moreover, figures 4-6 show shows the results of measurements of the frequency dependence of the complex dielectric constant of marsh vegetation for three species. We can see that real and imaginary part rise with a moisture increase. As for the behavior of the dielectric constant as a function of frequency, the following patterns were observed. Frequency dependence is weak at low moisture for all three species. Moisture values 3-5-8 % correspond to the dried plants, which are already unable to come to life. Non-monotonic behavior of the frequency dependence becomes apparent for more wetting samples, above 30 %. We can observe a resonance for 35.2 % at 3 GHz at figure 5 as increasing of imaginary part and relative decreasing of real part of complex permittivity. For 72.4 % the region increasing ε″ moves to 6 GHz. Another species of vegetation have similar resonances at other frequencies. Hydration above 80% corresponds to a plant with succulent stems and is characterized by high values of ε′ and ε″. The frequency dependence looks different for different plants. This can be explained by the structural features of the above-ground parts of plants. So lichen *Cladonia stellaris* consists of soft porous twigs that are the elastic at the same time and can absorb water well. Moss *Dicranum polysetum* has very soft twigs with a lot of small hairs. Ground cedar *Diphasiastrum complanatum* has rigid branches with small scales. The structure of plant fibers determines the ability to absorb and retain moisture, which is reflected in the reduced dependencies.

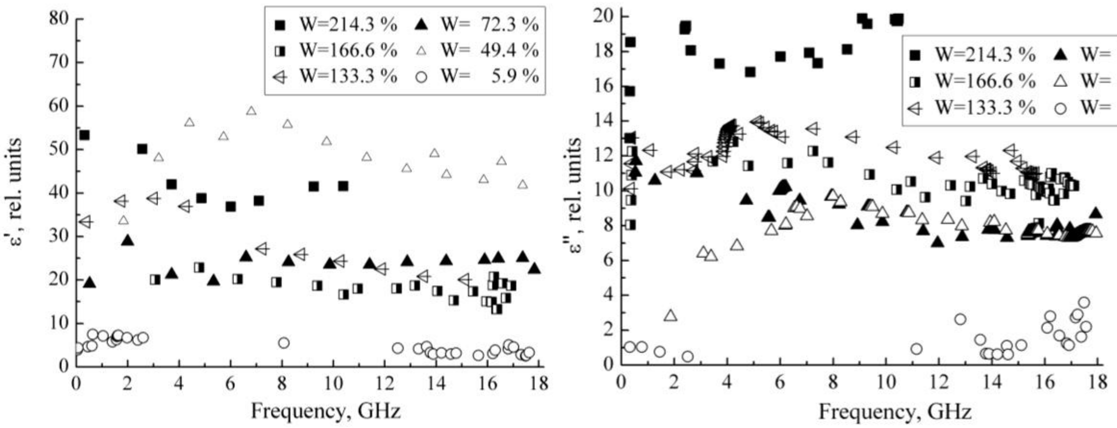

Figure 4. Frequency dependence of complex permittivity of moss (*Dicranum polysetum Michx*) at different moistures.

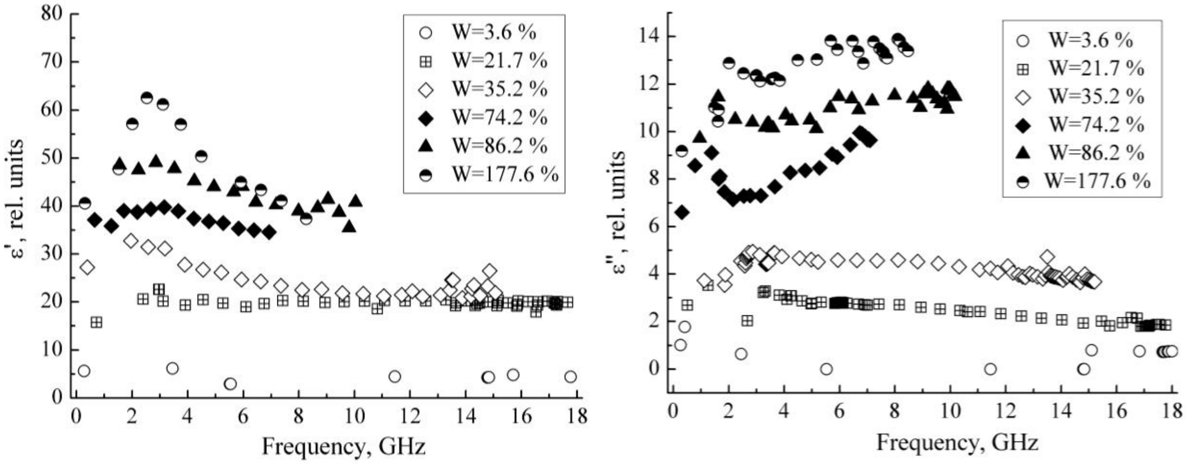

Figure 5. Frequency dependence of complex permittivity of ground cedar (*Diphasiastrum complanatum (L.) Holub*) at different moistures.

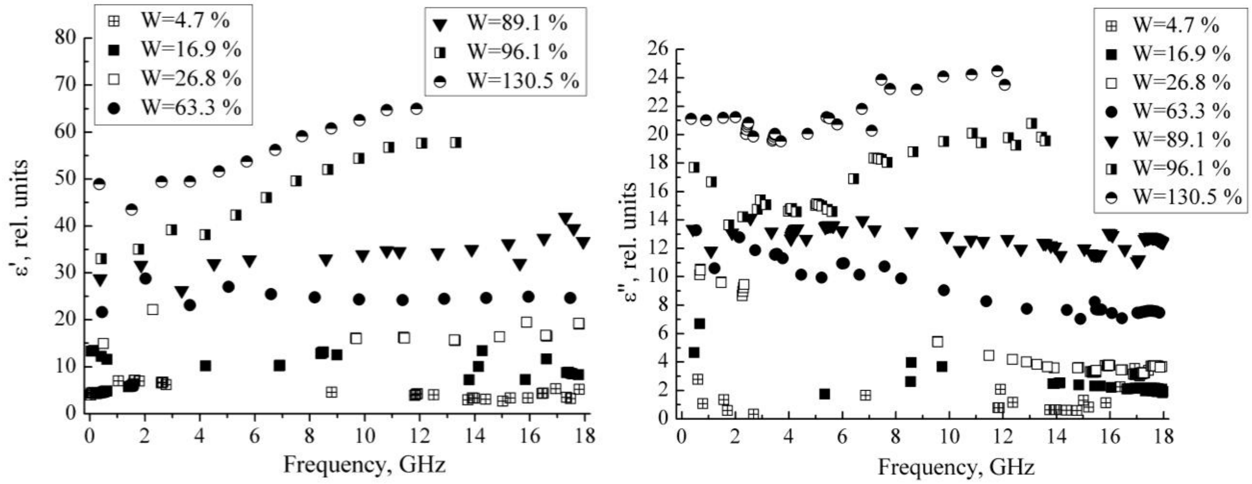

Figure 6. Frequency dependence of complex permittivity of lichen (*Cladonia stellaris*) at different moistures.

4. RESULTS

The water in the vegetation can be in three states (phases): in the cells, in the cell walls, and in the intercellular space. Two break point were observed corresponding to the transition of water in the vegetation in various phase states. Dependence of permittivity on moisture permits to determine these points.

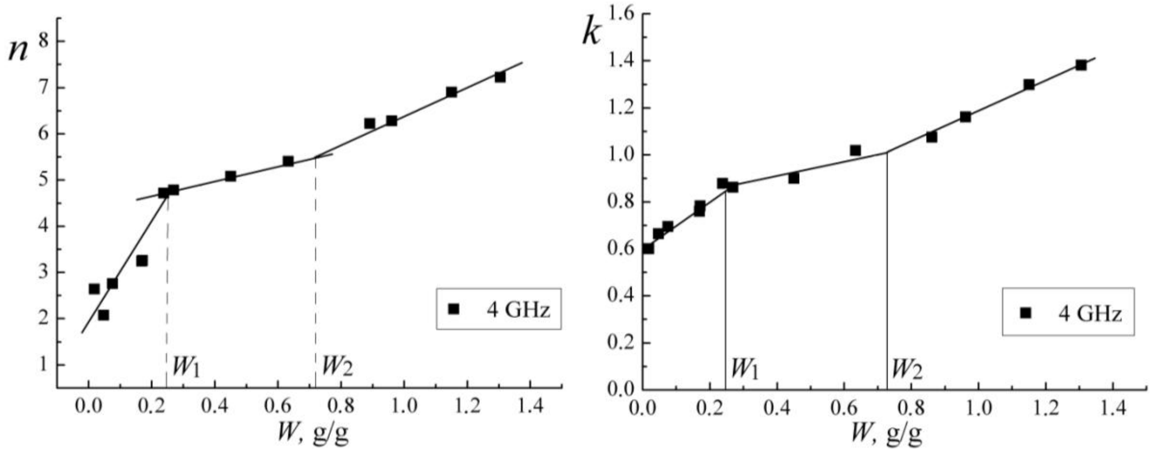

Figure 7. The dependence on weight moisture of refractive index *n* and absorption factor *k* for a moss at 4 GHz.

Author [11] used refractive model for the description of the dielectric characteristics of the wet vegetation, in particular wood. This model dates back to the Birchak formula [6] of composite theory and is well proven in modeling complex permittivity of soil [4, 5].The model is written as follows:

$$n=\sum_{i=1}^{m} W_i n_i\ ,\quad k=\sum_{i=1}^{m} W_i k_i\ , \tag{3}$$

where n_i and k_i – refractive index and absorption factor of composite and i-th component, W_i - volume fraction of and $_i$-th component. The soft part of the plant can be represented as a multiphase heterogeneous system, comprising the dry substance with n_0 and k_0, consisting of plant fibers, air and water, differing in phase composition equation (3) can be rewritten as follows:

$$n=\begin{cases} n_0+W(n_{w1}-1), & W\le W_1, \\ n_1+(W-W_1)(n_{w2}-1), & W_1\le W\le W_2, \\ n_2+(W-W_2)(n_{w3}-1), & W_2\le W, \end{cases} \tag{4}$$

$$k=\begin{cases} k_0+Wk_{w1}, & W\le W_1, \\ k_1+(W-W_1)k_{w2}, & W_1\le W\le W_2, \\ k_2+(W-W_2)k_{w3} & W_2\le W, \end{cases} \tag{5}$$

Where $n_2=n_1+(W-W_1)(n_{w2}-1)$, $k_1=k_0+Wk_{w1}$, $k_2=k_1+(W-W_1)k_{w2}$ – refractive index and absorption factor of marsh vegetation, wetting to volume moisture W_1 и W_1 relatively $n_{w1}...n_{w3}$ и $k_{w1}...k_{w3}$ - refractive index and absorption factor of different phase of water in plants.

To determine the dielectric model of the liquid located in the vegetation, the value of the complex dielectric constant was transferred to the refractive index and absorption by the formulas:

$$n=\sqrt{\tfrac{1}{2}(\varepsilon'+\sqrt{\varepsilon'^2+\varepsilon''^2})}\ ,\ k=\sqrt{\tfrac{1}{2}(-\varepsilon'+\sqrt{\varepsilon'^2+\varepsilon''^2})}\ . \tag{6}$$

Accoding [12]:

$$\frac{dn}{dW} = n_w - 1,\ \frac{dk}{dW} = k_w. \tag{7}$$

Different parts of the complex permittivity dependency on moisture were fitted by line for all frequency points. The slope of the approximation line determined values of the dielectric constant of the liquid in a vegetation. For example figure 7 shows moisture dependence of refractive index and absorption factor of moss *Dicranum polysetum* at 4 GHz. We can see two salient points.

The complex permittivity spectra of water in the vegetation allow determining the most likely corresponding dielectric model of water in the vegetation by the method of hypothesis testing. It is the Debye's model. Special software was developed at the Radiophysics Department TSU [13].

$$\varepsilon^* = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1 + j\omega\tau}. \tag{8}$$

where ε_∞ – contribution to ε', due to the electron and nuclear polarization; ε_0 – static dielectric constant; τ – relaxation time. This parameter corresponds to the Debye model, found numerically by the program are given in Tables 2 and 3.

Table 1. Debye model parameters for water in plants.

Type of water	Lichen Cladonia			Ground cedar Diphasiastrum			Moss Dicranum		
	ε_0	ε_∞	τ, ps	ε_0	ε_∞	τ, ps	ε_0	ε_∞	τ, ps
in the cells	80.5	26.5	149.08	132.9	214.0	9.28	163.1	140.2	12.86
in the cell walls	27.5	9.4	1294.08	81.4	186.4	1506.78	9.2	3.3	200.42
in the intercellular space	38.2	18.3	470.02	70.1	36.55	64.20	21.5	7.8	28.98

Table 2. The parameters of complex permittivity model of plants.

	n_0	k_0	W_1	W_2
Lichen	2.28	0.37	0.22	0.73
Groundcedar	2.62	0.11	0.21	0.72
Moss	1.95	0.42	0.25	0.75

The initial model parameters to zero moisture have weak dependence on the frequency, which in this model is not taken into account. Now we can calculate the dielectric constant of water at any frequency from our range 0.05 ÷ 18 GHz in any of three states, and to find complex permittivity of vegetation by the formulas of the model (4) – (5). Unfortunately, it is only at room temperature still. Figure 8 shows satisfactory compliance experimental and calculated data.

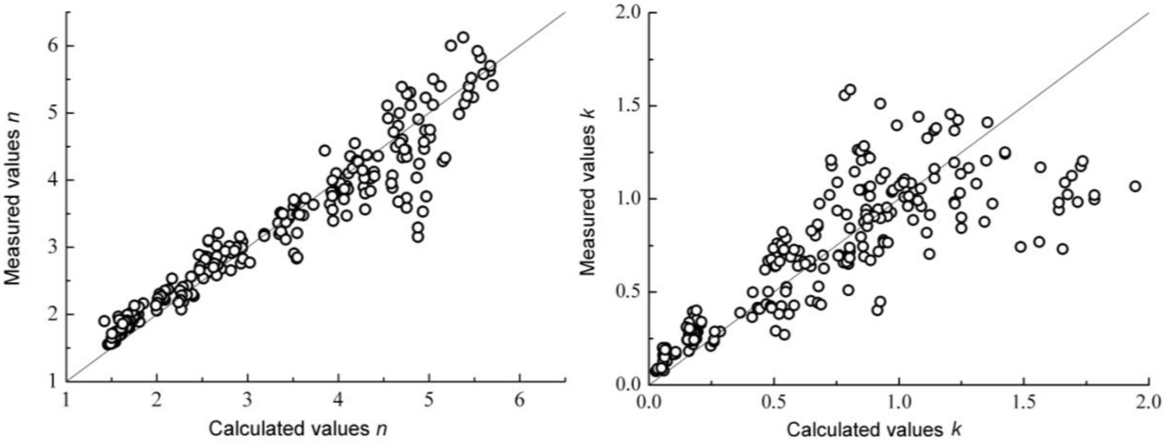

Figure 8. Correlations between calculated and measured values of refractive index *n* and absorption factor *k* for a ground cedar.

To estimate the accuracy of the model was built the calculated values dependence on the measured values. There is a systematic error that can be taken into account. A high correlation coefficient was obtained for values of dielectric constant. The dielectric loss has a more greater spread, however a correlation coefficient greater than 0.6 indicates a sufficient degree of correspondence between the calculated and measured values. Pearson coefficient for all samples of plants is given in Table 3.

Table 3. Pearson correlation coefficient for of complex permittivity model of plants.

	Lichen	Moss	Ground cedar
ρ for n	0.96782	0.94765	0.95470
ρ for k	0.77618	0.67899	0.70631

5. CONCLUSIONS

Values of permittivity for different species of vegetation with the same moisture differ markedly. Dielectric constant gives instrument to identify species of plants.

The water in the vegetation can be in three states (phases): in the cells, in the cell walls, and in the intercellular space. Two break point were observed corresponding to the transition of water in the vegetation in various phase states.

The complex permittivity spectra of water in the vegetation allow determining the most likely corresponding dielectric model of water in the vegetation. It is the Debye’s model.

Parameters of Debye’s model were obtained by numerical methods for all of three states of water. This enables to calculate the dielectric constant of water at any frequency range from 500 MHz to 18 GHz, and to find the parameters of the dielectric model of the vegetation.

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