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Статьи

Fire-induced changes in the dielectric constant of lichens in plateau palsas of the Nadym-Pur interfluve

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The paper analyzed the complex permittivity of lichens of the genus *Cladonia* sampled from areas disturbed by fire and from undisturbed plateau palsas in the Nadym-Pur interfluve, Western Siberia. The complex permittivity at microwave-frequency range was estimated by coaxial line measurement using an Agilent E8363B vector network analyzer. The real and imaginary parts of the permittivity of lichens in the disturbed areas were found to be significantly lower than ones of lichens from undisturbed areas. The linear dependence of the complex permittivity on water content is more pronounced in the lichen sampled from the disturbed areas. The obtained patterns can be used for radargram interpretation.

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Keywords

Complex permittivity, dielectric constant, forest fires, peatlands, plateau palsa, Western Siberia

Introduction

Plateau palsas, complexes of frost mounds, hollows and thermokarst lakes, cover significant areas of the northern taiga in Western Siberia (Pyavchenko 1955; Alekseeva, Khozyainova 2008). In the moss-lichen layer of frost mounds, lichens account for about 95% of the projective cover; lichens of the genus Cladonia dominate in the area (Meltzer 1985; Shishkonakova et al., 2016). Lichen cover is a complex heterophasic system that regulates nutritional, hydrothermal, and gas regimes of peatlands (Palmqvist 2000; Ten Veldhuis et al. 2017; Gauslaa 2014).

In recent decades, air temperature increase exacerbates the factors that create perfect fire conditions (Osterkamp and Romanovsky 1999; Rubtsov et al. 2010; Shvidenko and Schepashchenko 2013; Ponomarev and Kharuk 2016). In the period of 1985–2018, fires disturbed 10.5% of the forest-tundra area in the Nadym-Pur, Salekhard, and Nizhnevartovsk landscape provinces of Western Siberia (Moskovchenko et al. 2020). Wildfires are the most ecologically dangerous exogenous disturbances that can cause significant changes in landscapes, energy balance, and hydrothermal regime of soil and aboveground vegetation (Shvidenko et al. 2011; Bret-Harte et al. 2013; Jones et al. 2015; Miller et al. 2018; Li et al. 2019; Holloway et al. 2020). Peatland fires are supposed to transfer an average of 0.35–1 Gt/yr of terrestrial carbon to the atmosphere, providing a positive feedback that enhances climate warming (Page et al. 2002; Nechita-Banda et al. 2018; Nelson et al. 2021; Page et al. 2002). In addition, fires are undoubtedly one of the essential drivers of permafrost thaw (Kasischke and Turetsky 2006; Gibson et al. 2018).

Fires significantly change the properties of the lichen cover, including its composition, density, albedo, and the ability to sequester carbon, which, in turn, affects the food, hydrothermal and gas regime of peatlands, and the state of permafrost. Yet, these changes have been studied insufficiently (Johnson 1981; Klein 1982; Coxson, Marsh 2001; Boudreault et al. 2009; Miller et al. 2018).

Quantitative assessment of particularly heterogeneous landscapes in northern areas (Holloway et al. 2020) requires improved remote sensing systems to accumulate an array of multi-temporal data, including those obtained using unmanned aerial vehicles for radiometric surveys (Nikitin et al. 2008; Arkhipov, Nikitin 2011). The development of remote sensing methods for monitoring the vegetation cover state employs on the findings obtained for patterns of the interaction of electromagnetic waves with vegetation, and uses the dependences of the dielectric constant of vegetation on temperature, water content, and the plant water holding capacity (Parrens et al. 2016; Romanov 2017). The radio-emitting and reflectance characteristics of the areas at different frequencies depend on physical characteristics of vegetation: spatial heterogeneity of the ground vegetation cover entails a variability of the complex permittivity (Li et al. 2014; Romanov et al. 2017; Vadov and Sudakova 2017; Mavrovic et al. 2018). Many studies prove that different types of plants have completely different dielectric constants (Ulaby and Jedlicka 1984; Navarrete et al. 2011; Shrestha and Wood 2011; Mavrovic et al. 2018; Metlek et al. 2021). Previously, we have shown the complex permittivity dependences of some types of marsh vegetation on frequency, such as rosemary and lingonberry leaves, sedge, club moss, sphagnum mosses, and lichens of the genus *Cladonia* (Romanov et al. 2017; Kochetkova et al. 2015). This study is aimed at assessing changes in the complex permittivity of lichens in areas of the plateau palsa disturbed by fires and comparing them with undisturbed analogues, which will allow monitoring large areas of firedamaged areas using remote sensing, including those obtained using unmanned aerial vehicles for radiometric surveys.

Materials and methods

Sampling area

We studied the plateau palsa area in the Nadym-Pur interfluve. Part of the area was affected by wildfire in 2007, which significantly changed the vegetation cover and the thickness of the permafrost active layer (Fig. 1).

Lichen samples from the genus *Cladonia* were collected from the site disturbed by fire and from its undisturbed counterpart. Previously, the site was described in detail (Lojko et al. 2017; Kolesnichenko et al. 2019). Field studies were performed using the equipment of the unique research installation ‘System of experimental bases located along the latitudinal gradient’ from TSU under the financial support of the Ministry of Science and Higher Education of Russia (RF-2296.61321X0043, 13.UNU.21.0005, contract No. 075-15-2021-672). The equipment of the Center for Radiophysical Measurements, Diagnostics and Research of the Parameters of Natural and Artificial Materials of Tomsk State University was using in this research.

Complex permittivity measurement

The microwave-frequency complex permittivity of lichen samples was measured in the transmission line, namely, in the coaxial line, using an Agilent E8363B vector network analyzer. This measurement technique is employed to study the dielectric properties of soils and liquids and is described in the literature, for example in (Repin et al. 2008; Milkin et al. 2014; Bobrov et al. 2015 Kochetkova et al. 2015). We used the design pattern the design of the coaxial cell with the test sample placed inside (Fig. 2).

PTFE washers are used to confine bulk samples in the cell. The coaxial cell is connected to two ports of the vector network analyzer by torque wrench to ensure a constant cell length. We perform calibration in the beginning of measurement to eliminate the influence of cables and connectors. The diameter of the coaxial cells $d_{internal}$ = 3.06 mm and $d_{external}$ = 7 mm. In the experiment, a set of cells of different lengths was used: $l1$ = 17 mm, $l2$ = 37 mm, $l3$ = 57 mm, for samples of different water content. The measured scattering matrix values are used to calculate the real and imaginary parts of the permittivity based on the theory of wave propagation through layered media. Estimation of measurement error, a method for calculating the complex permittivity from the S-parameters of a coaxial cell are described in the article (Bobrov et al. 2015). Measurement error is from 0.4% to 2%.

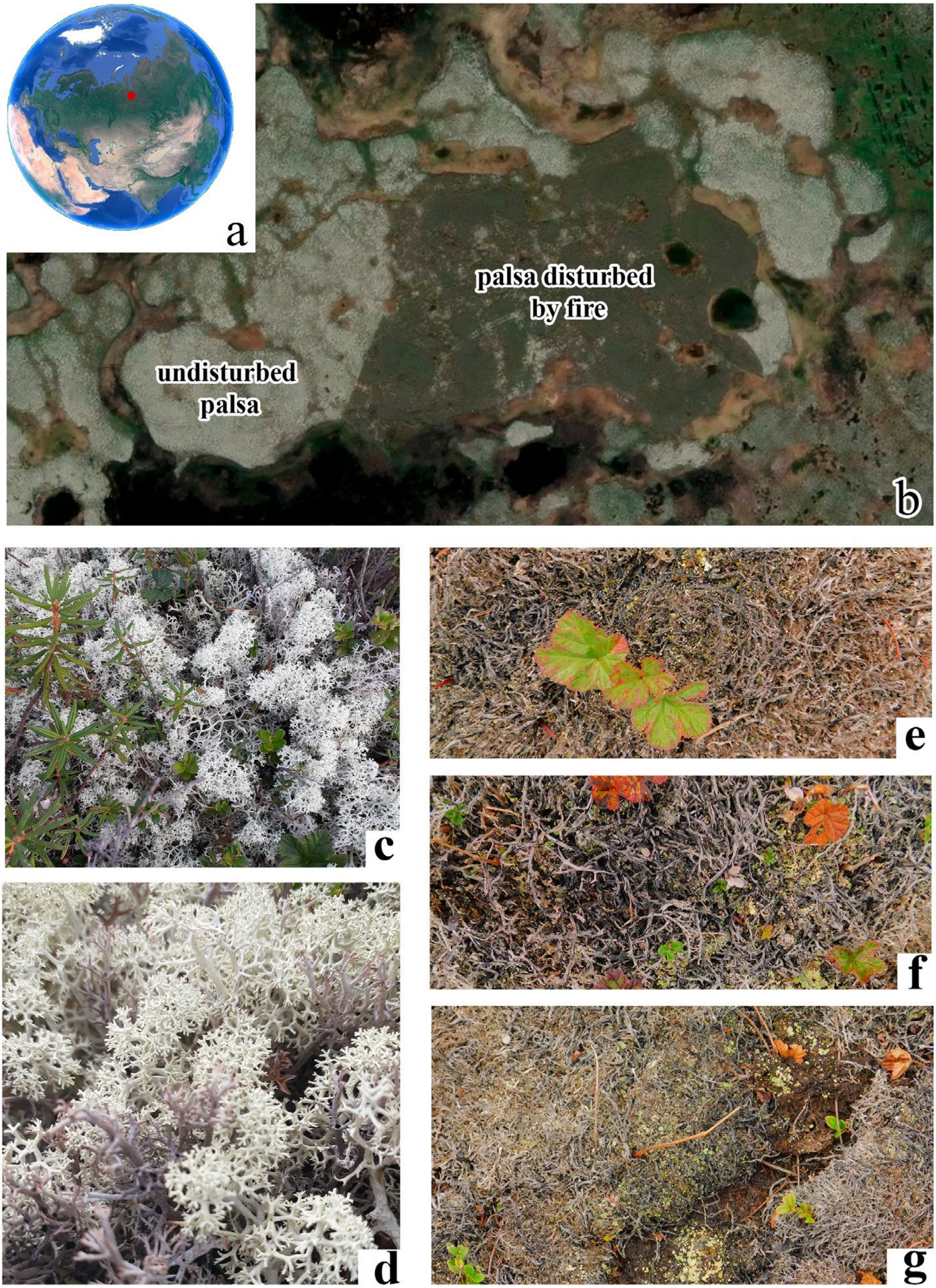

a
palsa disturbed
by fire
undisturbed
palsa
b
c
d
e
f
g

Figure 1. ***Figure 1.*** *Sampling area. a – sampling site location, b – satellite image of the sampling site (Google Earth), c, d – lichen cover of undisturbed palsa, e, f, g – lichen cover of palsa disturbed by fire.*

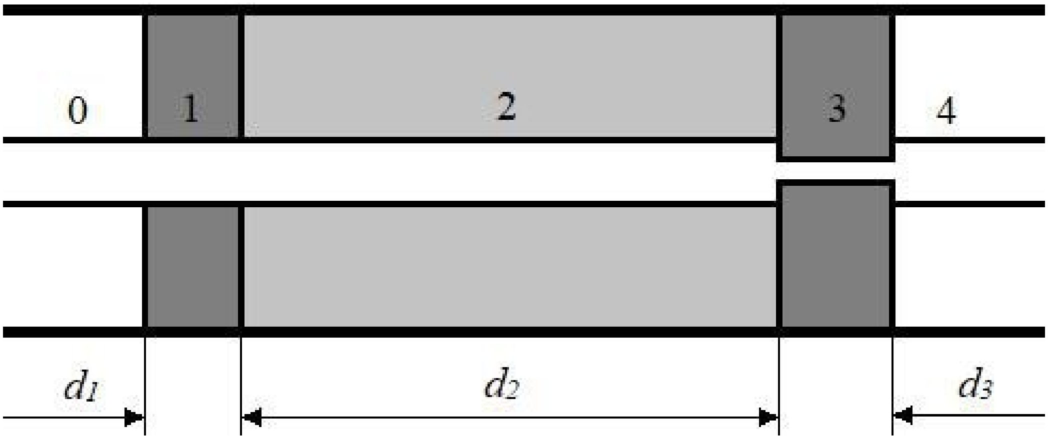


Figure 2. ***Figure 2.*** *Layout of sample placement in the cell.*

The complex permittivity was studied at frequencies of 1.20, 1.40, 2.56, 5.40 and 9.00 GHz for 26 Lichen samples from the genus *Cladonia*.

The water content of the samples was obtained as gravimetric water by weighing wet and dry samples dried to constant weight. Electronic scales Shimadzu AY 22 are used.

Statistical methods

Statistical data were processed and graphical models were developed using Statistica 8.0. The methods of nonparametric statistics (Wilcoxon criterion, Spearman correlation) and regression analysis were used. In the statistical analysis, samples of burnt and unburnt lichens of similar water content were estimated.

Result

It was established that both the imaginary and real parts of the permittivity of lichens in disturbed areas are somewhat lower than that in undisturbed areas (Table 1, Figure 3), which is confirmed by the Wilcoxon criterion (Z= 2.02, p= 0.04).

In both cases, frequency dependence of the dielectric constant is not apparent and is more distinct at high water content values, which corresponds to the physical idea of a more intense interaction of electromagnetic radiation with free state water (Romanov et al. 2017). Unburnt lichen exhibits a non-monotonic dependence; two culminating points can be clearly observed at 50% and 90% water content. This can be due to a different bonding degree between water molecules. Burnt lichen does not exhibit such pronounced transitions in the water content dependence of the complex permittivity, which indicates a more uniform material structure.

In the test samples, both real and imaginary parts of the permittivity increase as water content grows (Figure 3, Table 2). A linear dependence of the permittivity on water content is more pronounced in burnt lichen.

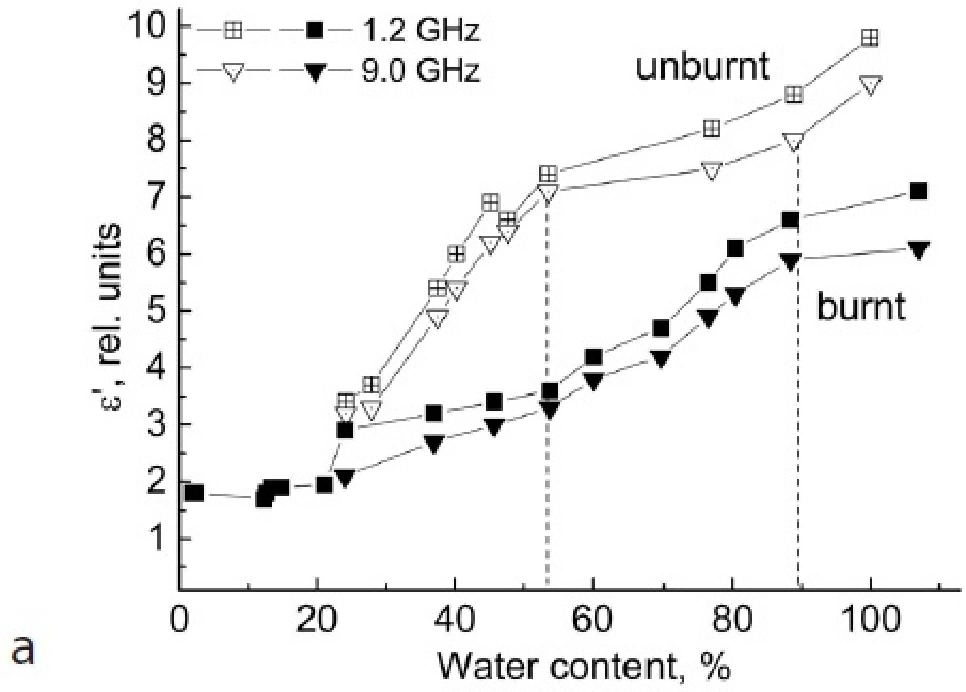
Water content, %	1.20 GHz		1.40 GHz		2.56 GHz		5.40 GHz		9.00 GHz	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
Lichen samples taken from disturbed palsa										
24.05	2.90	1.10	2.80	0.79	2.70	0.75	2.12	0.90	2.10	1.00
36.93	3.20	1.30	3.10	1.20	3.00	1.10	2.85	1.00	2.70	0.90

45.69	3.40	1.40	3.40	1.20	3.30	1.20	3.15	1.10	3.00	1.00
53.74	3.60	1.95	3.50	1.85	3.40	1.75	3.30	1.60	3.30	1.65
60.11	4.20	2.25	4.10	2.15	4.05	2.00	3.90	1.90	3.80	1.85
69.59	4.70	2.70	4.50	2.60	4.40	2.40	4.30	2.20	4.20	2.20
76.42	5.50	3.10	5.40	3.00	5.30	2.85	5.10	2.75	4.90	2.50
80.34	6.10	3.40	6.00	3.30	5.80	3.15	5.60	3.05	5.30	2.80
88.37	6.60	3.70	6.40	3.50	6.20	3.30	6.00	3.10	5.90	3.00
Lichen samples taken from undisturbed palsa										
24.17	3.40	1.00	3.35	0.95	3.30	0.93	3.10	0.91	3.20	0.83
27.89	3.70	0.97	3.40	0.95	3.50	0.88	3.40	0.82	3.30	0.85
37.48	5.40	1.73	5.30	1.68	5.20	1.60	5.00	1.50	4.90	1.55
40.24	6.00	1.80	5.90	1.70	5.65	1.65	5.45	1.55	5.40	1.65
45.14	6.90	2.13	6.70	1.98	6.60	1.80	6.20	1.75	6.20	1.70
47.65	6.60	2.00	6.60	1.92	6.50	1.91	6.10	1.71	6.40	1.92
53.52	7.40	3.20	7.30	3.15	7.20	3.15	7.05	2.80	7.10	2.33
76.97	8.20	3.80	8.00	3.30	7.90	2.90	7.80	2.45	7.50	2.30
88.86	8.80	5.00	8.60	4.70	8.30	4.40	8.00	4.20	8.00	4.00
100.01	9.80	6.30	9.50	6.00	9.40	5.40	9.30	5.15	9.00	5.00

Table 1. *Complex permittivity of burnt and unburnt lichen from the genus Cladonia.* Notes: ε' – real part of complex permittivity; ε'' – imaginary part of complex permittivity.

Frequencies, GHz	Burnt lichen samples			Unburnt lichen samples		
	r	R^2	Regression equation	r	R^2	Regression equation
Real part of the permittivity						
1.20	0.96	0.79	$w= 15.9e^{0.23\varepsilon'}$	0.94	0.96	$w= 11.1e^{0.24\varepsilon'}$
1.40	0.96	0.80	$w= 15.9e^{0.29\varepsilon'}$	0.94	0.96	$w= 11.3e^{0.22\varepsilon'}$
2.56	0.96	0.80	$w= 15.7e^{0.30\varepsilon'}$	0.94	0.96	$w= 11.1e^{0.23\varepsilon'}$
5.40	0.98	0.88	$w = 16.6e^{0.30\varepsilon'}$	0.95	0.97	$w = 11.7e^{0.23\varepsilon'}$
9.00	0.98	0.88	$w = 16.4e^{0.31\varepsilon'}$	0.93	0.96	$w = 11.3e^{0.24\varepsilon'}$
Imaginary part of the permittivity						
1.20	0.98	0.86	$w = 21.5e^{0.41\varepsilon''}$	0.98	0.90	$w = 24.1e^{0.26\varepsilon''}$
1.40	0.99	0.89	$w = 23.1e^{0.40\varepsilon''}$	0.97	0.89	$w = 24.2e^{0.27\varepsilon''}$
2.56	0.99	0.90	$w = 23.0e^{0.43\varepsilon''}$	0.96	0.87	$w = 23.6e^{0.30\varepsilon''}$
5.40	0.97	0.84	$w = 23.4e^{0.44\varepsilon''}$	0.95	0.84	$w = 24.3e^{0.31\varepsilon''}$
9.00	0.96	0.81	$w = 22.8e^{0.47\varepsilon''}$	0.95	0.84	$w = 23.8e^{0.33\varepsilon''}$

Table 2. *Dependence of the permittivity on water content ($p < 0.01$).* Notes: *w* – water content, %; ε' – real part of the permittivity, relative units, ε'' – imaginary part of the permittivity, relative units.



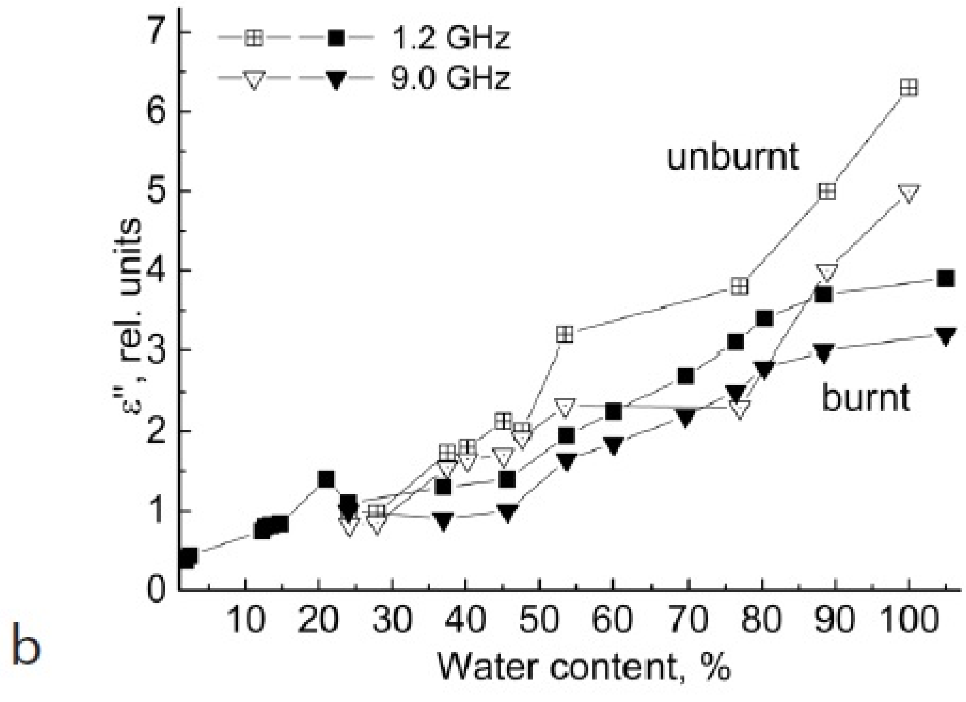


Figure 3. ***Figure 3.*** *Dependence of the permittivity of burnt and unburnt lichen on water content at frequencies of 1.2 GHz and 9.0 GHz; a – real part, b – imaginary part.*

Relationship between the real/imaginary parts of complex permittivity of all vegetation and their gravimetric moisture can fit well with a simple base e exponential function, as noted earlier for other plant species (Li et al. 2013).

Lichens possess unique strategies developed to control gas-liquid transport between an algal photobiont and its host fungus (Ten Veldhuis et al. 2017, 2018; Potkay et al. 2020). The species belong to poikilohydric organisms in which water status is dependent on ambient humidity and is extremely variable (Golovko et al. 2018, 2020). At high humidity, water content of lichens is known to be 2–3 fold higher than the dry weight (Green et al. 2008), whereas at humidity of 5–10%, they go into cryptobiosis (Slonov et al. 2009). Stress repair mechanisms help lichens quickly restore their functions after dehydration (Kappen and Valladares 1999; Beckett et al. 2008). As humidity changes, lichens release absorbed water to moderate the hydrological dynamics of peatlands (Gauslaa 2014). Fires change the strategies for controlling gas-liquid transport, but the mechanisms of these changes have not yet been studied.

The revealed dependences can help estimate water content of lichens in both disturbed and undisturbed large plateau palsas by remote sensing methods, including the use of unmanned aerial vehicles hosting a microwave radiometer. The intensity of lichen photosynthesis and respiration depends on their water content: the photosynthesis periods are limited by duration and frequency of their hydrated periods, and a lack of water and thalli drying decrease photosynthetic CO_2 assimilation (Palmqvist & Sundberg 2000; MacKenzie et al. 2001; Dahlman & Palmqvist 2003; Golovko et al. 2020). Thus, the dielectric constant can help estimate both water content of lichens and greenhouse gas emissions over large areas.

Conclusions

It was found that both the imaginary and real parts of the dielectric constant of lichens in the areas disturbed by fire are somewhat lower than the dielectric constant of lichens in undisturbed areas. In lichens sampled from the disturbed area, the linear dependence of the dielectric constant on water content is more apparent. The revealed dependences can help estimate water content of lichens in large disturbed and undisturbed plateau palsas using remote sensing methods (Parrens et al. 2016; Romanov 2017). In addition, comparison of the values of water content and photosynthetic CO_2 assimilation, as well as remote sensing methods used, can help estimate CO_2 assimilation over large areas.

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