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Hybrid Mode Dispersion Characteristic Dependences of Cylindrical Dipolar Glass Waveguides on Temperatures

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Introduction

Circular cylindrical waveguides for many years were investigated and used due to their excellent electrodynamical characteristics like a large broadbandwidth and the wide possibilities for their application in microwave solid-state electronics. Today, researchers are engaged in exploring and developing new materials with special properties that can be used in microwave electronics [1–4].

Advanced specialty glasses play important roles in modern advance technologies. In the last several years, these materials have continued to find new applications in the areas of telecommunications, electronics and biomedical uses. The mixed crystal $Rb_{1-x}(ND_4)_xD_2PO_4$ [DRADP-x] have a dipolar glass phase at the low temperature when the mixing concentration x between the ferroelectric RbD_2PO_4 and the antiferroelectric $ND_4D_2PO_4$ is in the range $0.3 \le x \le 0.7$. This is one of more thoroughly investigated dipolar glass systems [5, 6].

Here we present for the first time the dispersion characteristic analysis of open circular dipolar glass waveguides (Fig. 1) at the temperatures $130 \le T \le 200\,\mathrm{K}$.

We demonstrate here the complex longitudinal propagation constants of the main mode in the frequency range from 1 GHz to 150 GHz for four values T when the waveguide radius is $R = 1\,\mathrm{mm}$. We give the propagation constant dependencies when waveguides have radii equal to 1 mm, 2 mm, 3 mm at $T = 150\,\mathrm{K}$. We present the dispersion characteristics of main HE_{11} and two higher EH_{11} and HE_{12} hybrid modes of the waveguide with the radius equal to 1 mm at $T = 150\,\mathrm{K}$.

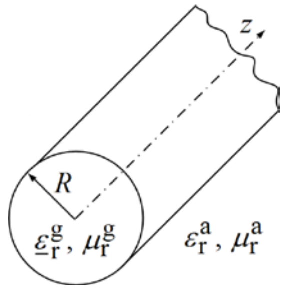

Fig. 1. The cylindrical dipolar glass waveguide model

We demonstrate here also the waveguide broadbandwidth dependencies on the temperatures ($130 \le T \le 200\,\mathrm{K}$) at three waveguide radii 1 mm, 2 mm and 3 mm. We discovered several important features of the dipolar glass waveguides that could be used for working out the microwave devices.

Dispersion equation

For the solution of our electrodynamical problem we used the Maxwell's equations in this form

$$\begin{cases} \nabla \times \underline{\boldsymbol{E}} = -\mathrm{i}\omega\mu_r^g \mu_0 \underline{\boldsymbol{H}}, \\ \nabla \times \underline{\boldsymbol{H}} = \mathrm{i}\omega\underline{\varepsilon}_r^g \varepsilon_0 \underline{\boldsymbol{E}}, \end{cases} \quad (1)$$

where $\underline{\boldsymbol{H}}$ is the magnetic field strength, $\underline{\boldsymbol{E}}$ is the electric field strength. The complex dispersion equation of the cylindrical lossy waveguide for analizing of the full spectrum eigenmodes is:

$$
\begin{aligned}
\underline{\Delta} = & \left(\frac{m\underline{h}}{\left(\underline{k}_{\perp}^{a}\right)^{2} R} J_m(\underline{k}_{\perp}^{g} R) \cdot H_m^{(2)}(\underline{k}_{\perp}^{a} R) \right)^2 + \\
& + \left(\frac{m\underline{h}}{\left(\underline{k}_{\perp}^{g}\right)^{2} R} J_m(\underline{k}_{\perp}^{g} R) \cdot H_m^{(2)}(\underline{k}_{\perp}^{a} R) \right)^2 - \\
& - \frac{\omega^2 \varepsilon_0 \mu_0 \underline{\varepsilon}_r^{g} \mu_r^{g}}{\left(\underline{k}_{\perp}^{g}\right)^{2}} \left(J'_m(\underline{k}_{\perp}^{g} R) \cdot H_m^{(2)}(\underline{k}_{\perp}^{a} R) \right)^2 - \\
& - \frac{\omega^2 \varepsilon_0 \mu_0 \varepsilon_r^{a} \mu_r^{a}}{\left(\underline{k}_{\perp}^{a}\right)^{2}} \left(J_m(\underline{k}_{\perp}^{g} R) \cdot H_m'^{(2)}(\underline{k}_{\perp}^{a} R) \right)^2 - \\
& - 2 \left(\frac{m\underline{h}}{\underline{k}_{\perp}^{g} \underline{k}_{\perp}^{a} R} \right)^2 \left(J_m(\underline{k}_{\perp}^{g} R) \cdot H_m^{(2)}(\underline{k}_{\perp}^{a} R) \right)^2 + \\
& + \frac{\omega^2 \varepsilon_0 \mu_0 \varepsilon_r^{a} \mu_r^{g}}{\underline{k}_{\perp}^{g} \underline{k}_{\perp}^{a}} J_m(\underline{k}_{\perp}^{g} R) \cdot J'_m(\underline{k}_{\perp}^{g} R) \cdot H_m^{(2)}(\underline{k}_{\perp}^{a} R) \cdot H_m'^{(2)}(\underline{k}_{\perp}^{a} R) + \\
& + \frac{\omega^2 \varepsilon_0 \mu_0 \underline{\varepsilon}_r^{g} \mu_r^{a}}{\underline{k}_{\perp}^{g} \underline{k}_{\perp}^{a}} J_m(\underline{k}_{\perp}^{g} R) \cdot J'_m(\underline{k}_{\perp}^{g} R) \cdot H_m^{(2)}(\underline{k}_{\perp}^{a} R) \cdot H_m'^{(2)}(\underline{k}_{\perp}^{a} R),
\end{aligned}
\quad (2)
$$

where $J_m(\underline{k}_{\perp}^{g} R)$ is the Bessel function of the m-th order, $\underline{k}_{\perp}^{g} = \sqrt{k^2 \underline{\varepsilon}_r^{g} \mu_r^{g} - \underline{h}^2}$ is the transversal propagation constant for the dipolar glass medium, R is the waveguide radius, $H_m^{(2)}(\underline{k}_{\perp}^{a} R)$ is the Hankel function of the second kind, $\underline{k}_{\perp}^{a} = \sqrt{\underline{h}^2 - k^2 \underline{\varepsilon}_r^{a} \mu_r^{a}}$ is the transversal propagation constant in air, m is the azimuthal index. The value $k = \omega/c$ is the wave number in a vacuum, $\omega = 2\pi f$, where f is an operating frequency. The magnitude $\underline{\varepsilon}_r^{g} = \varepsilon_r^{g'} - i\varepsilon_r^{g''}$ is the complex permittivity of the dipolar glass, $\mu_r^{g} = 1$ is the glass permeability, $\varepsilon_r^{a} = 1$ and $\mu_r^{a} = 1$ are the permittivity and the permeability of air.

The complex permittivity $\underline{\varepsilon}_r^{g}$ dependencies on the frequency and the temperature are very complicated. For this reason in Fig. 2 we present the curves of values $\varepsilon_r^{g'}$, $\varepsilon_r^{g''}$ at the four temperatures in the wide frequency range 1—160 GHz. The curves are drawn on the base of the experimental data and formulae of article [5].

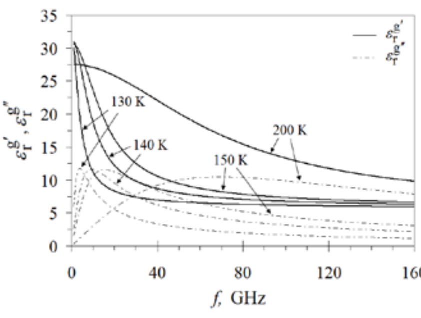

Fig. 2. The real $\varepsilon_r^{g'}$ and imaginary $\varepsilon_r^{g''}$ parts of the dipolar glass permittivity dependencies on the frequency at four temperatures T = 130 K, 140 K, 150 K and 200 K

Other magnitudes of the dispersion equation (2) are expressed in the form: the complex longitudinal propagation constant is $\underline{h} = h' - ih''$, where $h' = \mathrm{Re}(\underline{h})$ is the real part of the complex longitudinal propagation constant (rad/m), $h'' = \mathrm{Im}(\underline{h})$ is the imaginary part of the one (rad/m = 8.7 dB/m). Here $h' = 2\pi/\lambda_w$, where λ_w is the wavelength of the waveguide modes. In our calculations an azimuthal index is $m = 1$, because the main waveguide mode HE_{11} has the index equal to unity.

Dispersion characteristic analysis of the open dipolar glass waveguides

In the Fig. 3 and Fig. 5 we see the normalized real part of propagation constant h'/k upon frequency *f*. In Fig. 3 is shown the propagation constant dependencies of open dipolar glass cylindrical waveguide with the radius R = 1 mm on the frequency at four temperatures 130 K, 140 K, 150 K and 200 K. The frequency range is from 1 GHz to 150 GHz. We see that the propagation constant curves (Fig. 3) are similar at all temperatures. The cutoff frequencies of main mode of the waveguide at the T = 130 K, 140 K, 150 K and 200 K are 36.2 GHz, 14.2 GHz, 13.1 GHz and 15.4 GHz correspondingly. The character of propagation constant curves of open dipolar glass waveguide is strongly different in comparison with other open cylindrical dielectric waveguides [3, 7]. The magnitude h' increasing rapidly with increasing the frequency (*f* till 45—60 GHz) and after that the value h' changes feeble. The maximum of curves (Fig. 3) shifts to the lower frequency when the temperature increases.

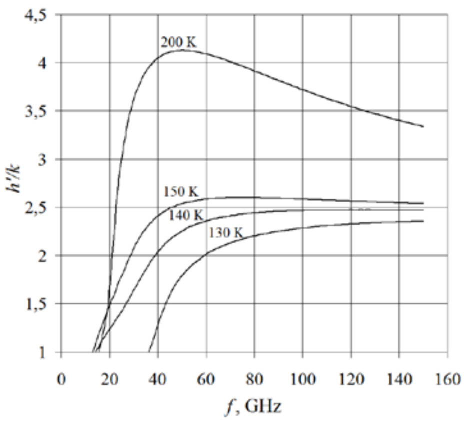

Fig. 3. Dependences of the waveguide normalized propagation constant on the frequency for the main modes at four temperatures, when the waveguide radius is R = 1 mm

In Fig. 4 is shown the waveguide losses at four temperatures. The losses at the beginning of growing *f* decrease till the minimum and after that they slowly increase at the temperatures 130 K, 140 K, 150 K and the losses pretty fast increase at 200 K. The behavior of dependencies at the high temperature 200 K differs from dependencies at low temperatures $130 \le T \le 150\,\mathrm{K}$ (Fig. 3 and 4). We see that the complex propagation constant changes insignificantly at the temperatures 130—150 K when frequencies are approximately between 60 GHz and 150 GHz. That means that the microwave devices worked out on the base of the dipolar glass waveguide at $130 \le T \le 150\,\mathrm{K}$ could operate stably.

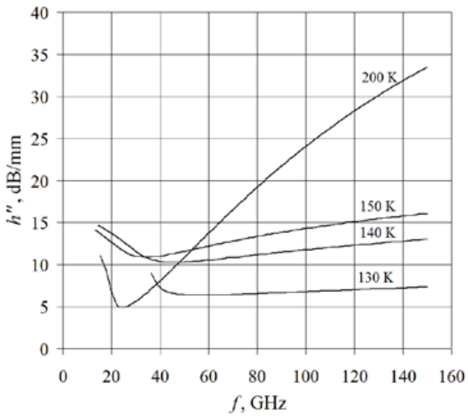

Fig. 4. Dependences of the waveguide losses on the frequency for the main modes at four temperatures, when the waveguide radius is R = 1 mm

Fig. 5 and Fig. 6 shows the dispersion characteristics of the main mode of the dipolar glass waveguides with radii equal to 1 mm, 2 mm and 3 mm at $T = 150\,\mathrm{K}$. We see that with increasing of the waveguide radius, the main mode cutoff frequency decreases. The cutoff frequencies of the waveguides with R = 1 mm, 2 mm and 3 mm are 13.1 GHz, 6.5 GHz and 4.6 GHz correspondingly. In Fig. 6 is shown that the minimum of the waveguide losses shifts to the higher frequencies when the radius becomes smaller.

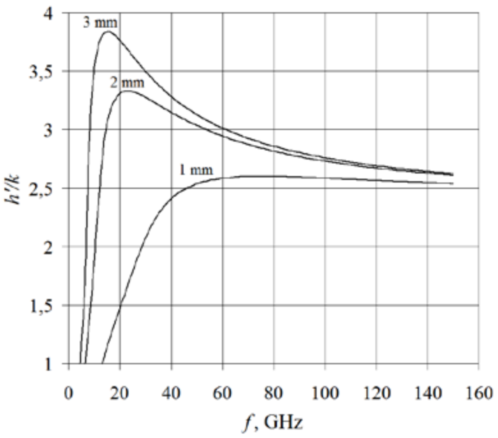

Fig. 5. Dependences of the waveguide normalized propagation constant on the frequency for the main modes at three waveguide radii equal to 1 mm, 2 mm and 3 mm when T = 150 K.

In Fig. 6 we see the larger waveguide radius is the lower main mode losses are at the analyzed frequency range.

In Fig. 7 are presented dependences of the waveguide propagation constant of the main mode HE_{11}, the first higher mode EH_{11} and the second higher mode HE_{12} on the frequency. In order to determine the waveguide broadbandwidth we have to know the cutoff frequencies of the main mode HE_{11} and the first higher mode EH_{11}. The broadbandwidth we calculated by algorithm given in [7].

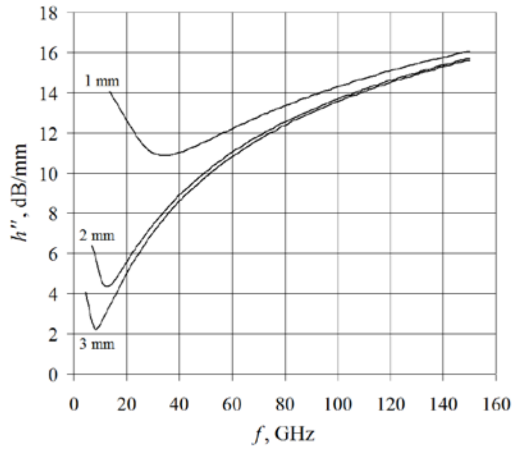

Fig. 6. Dependences of the waveguide losses on the frequency for the main modes at three waveguide radii equal to 1 mm, 2 mm and 3 mm when T = 150 K

In Fig. 8 are shown the broadbandwidth dependencies of the waveguides with radii 1 mm, 2 mm and 3 mm on the temperature. Broadbandwidth was calculated at four temperatures 130 K, 140 K, 150 K, and 200 K.

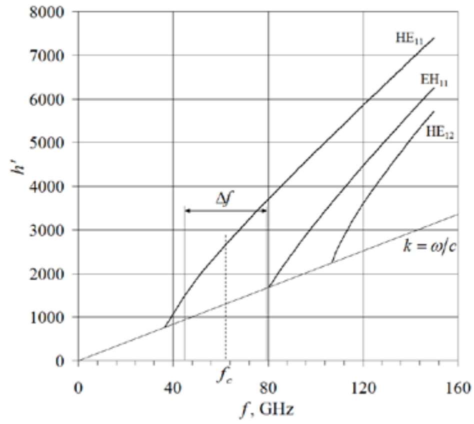

Fig. 7. Dispersion dependencies of the hybrid modes HE_{11}, EH_{11}, HE_{12} of the dipolar glass waveguide with R = 1 mm at T = 130 K

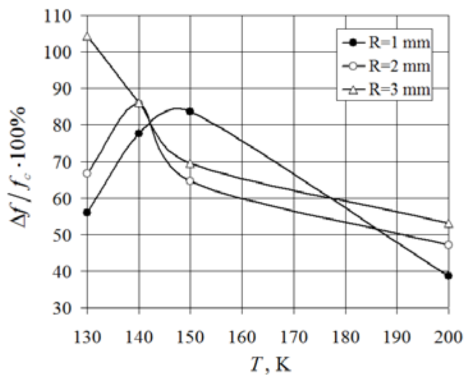

Fig. 8. Waveguide broadbandwidth dependencies on the temperature at the waveguide radii 1 mm, 2 mm and 3 mm

The magnitude $\Delta f = \left(f_{\mathrm{cut(EH_{11})}} - f_{\mathrm{cut(HE_{11})}} \right)$ is the waveguide operating frequency band, where $f_{\mathrm{cut(EH_{11})}}$ is the cutoff frequency of the first higher mode and $f_{\mathrm{cut(HE_{11})}}$ is the cutoff frequency of the main mode. The magnitude $f_C = \left(f_{cut(EH_{11})} + f_{cut(HE_{11})} \right) / 2$ is the central frequency of the operating frequency band is determined as the arithmetical average of the cutoff frequency of modes HE_{11} and EH_{11}. The broadbandwidth is calculated as the relationship in percentages between the waveguide operating frequency band and its central frequency according to the expression: $(\Delta f / f_C) \cdot 100\%$. As we can see (Fig. 8) the broadbandwith is highly dependent on the temperature as well as on the waveguide radius. We can select the temperature for a dipolar glass cylindrical waveguide with a certain radius that the waveguide broadbandwith would have the maximum.

Conclusions

We created a computer program and investigated the dispersion characteristics and the broadbandwidth of the open dipolar glass cylindrical waveguides at four temperatures (130 K, 140 K, 150 K and 200 K) and three waveguide radii (1 mm, 2 mm and 3 mm) in the wide frequency range from 1 GHz to 150 GHz.

We found that the complex propagation constant changes insignificantly at the temperatures 130—150 K when the frequencies are between 60 GHz and 150 GHz. This fact can be used for creation of the microwave devices on the base of the dipolar glass (Fig. 3 and Fig. 4).

We found that the cutoff frequency of the main hybrid mode HE_{11} strongly dependent on the temperature. This feature can be used to worked out of a microwave switch by the changing of the temperature in the interval $130 \le T \le 150\,\mathrm{K}$. (Fig. 3).

We notice that the waveguide losses are smaller when the waveguide radius is larger. It happened because the larger waveguide radius is the greater amount of microwave mode energy distributed in the air space outside the waveguide (Fig. 6).

We discovered that the waveguide broadbandwidth can be up to 100%. The broadbandwidth width can be controlled by the temperature changing (Fig. 8).

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In this work for the first time we present the dispersion characteristic analysis of open circular dipolar glass waveguides at the temperatures $130 \le T \le 200\,\mathrm{K}$ We demonstrate here the complex longitudinal propagation constants of the main mode HE_{11} in the frequency range from 1 GHz to 150 GHz for four values *T* when the waveguide radius is *R* = 1 mm. We give the propagation constant dependencies when waveguides have radii equal to 1 mm, 2 mm, 3 mm at *T* = 150 K. We present the dispersion characteristics of main HE_{11} and two higher hybrid EH_{11} and HE_{12} modes of the waveguide with the radius equal to 1 mm at *T* = 130 K. We demonstrate here also the waveguide broadbandwidth dependencies on the temperatures at three waveguide radii 1 mm, 2 mm and 3 mm. We discovered several important features of the dipolar glass waveguides that could be used for working out the microwave devices. Ill. 8, bibl. 7 (in English; abstracts in English and Lithuanian).

S. Ašmontas, L. Nickelson, A. Bubnelis, R. Martavičius, J. Skudutis. Hibridinių modų dispersinių charakteristikų priklausomybė nuo temperatūros cilindriniuose dipolinio stiklo bangolaidžiuose // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 10(106). – P. 83–86.

Šiame darbe pirmą kartą pateikiamos iš dipolinio stiklo pagaminto atvirojo cilindrinio bangolaidžio dispersinės charakteristikos, temperatūrų intervale $130 \le T \le 200\,\mathrm{K}$. Pateikiama pagrindinės modos HE_{11} kompleksinė išilginė bangos sklidimo konstanta esant keturioms *T* vertėms, plačiame dažnių ruože nuo 1 GHz iki 150 GHz bangolaidyje, kurio spindulys *R* = 1 mm. Nustatytos sklidimo konstantos priklausomybės 1 mm, 2 mm, 3 mm spindulio bangolaidžiuose, kai *T* = 150 K. Pateikiamos pagrindinės modos HE_{11} ir dviejų aukštesniųjų hibridinių modų EH_{11} ir HE_{12} dispersinės charakteristikos, kai *T* = 130 K, bangolaidyje, kurio spindulys lygus 1 mm. Taip pat parodoma tokio bangolaidžio plačiajuostiškumo priklausomybė nuo temperatūros ir bangolaidžio spindulio verčių. Atrastos kelios svarbios bangolaidžių iš dipolinio stiklo savybės, kurios gali būti pritaikytos kuriant įvairius mikrobangų įtaisus. Il. 8, bibl. 7 (anglų kalba; santraukos anglų ir lietuvių k.).