The Influence of Temperature on Microstrip Transmission Line Characteristics

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Abstract – **A mathematical temperature model of propagation characteristics is presented and its study is performed on the example of a microstrip transmission line. It was found that the maximum change of line characteristics with the separate influence of a temperature change from minus 50°C to 150°C on each of the cross-section parameters of the line does not exceed 1%, and with a simultaneous influence on all parameters – 10.76%. It was revealed that the maximum influence on the change of line characteristics is exerted by the change of the substrate relative dielectric permittivity, at which the maximum change in per-unit-length parameters is up to 10%.**

Index Terms – **climatic environment, ambient temperature, thermal expansion, per-unit-length parameters, microstrip line.**

I. Introduction

RADIOELECTRONIC EQUIPMENT (REE) has found its application in almost all spheres of modern society, the most important of which are military and aerospace. In such spheres REE operates in particularly difficult and often hard climatic environment, which can have a negative impact on it. For example, in near-earth orbit the metal warms up to 160 °C under direct sunlight and cools down to minus 100 °C in the shadow. A change of environment temperature can lead to a change in the chemical-physical and mechanical properties of materials [1]. With the temperature increase, the growth of some material defects accelerates, which leads to a decrease of the bounding strength of construction elements of the equipment. In addition, most materials in simultaneous exposure of heat and mechanical stress are subject to deformation. In a number of materials, heating causes chemical decomposition and accelerated aging, which result in a change in their parameters and characteristics. For example, due to the high relative permittivity of water during the operation of REE in a humid environment, a capacitive effect occurs, which manifests itself in a change in the surface resistance of insulators, capacitance and quality factor, and also in a decrease of a breakdown voltage, which can have a significant adverse effect on the sensitivity of REE. In this regard, considering the effect of temperature in the process of designing of REE is extremely relevant.

II. Problem Statement

Depending on the application field of the REE, climatic tests are carried out in the corresponding environment, and materials are selected to meet the technical requirements [2]. Meanwhile, conducting the full-scale climate tests requires a lot of time and financial costs, so the possibility to take into account climatic factors at an early stage of the device design will minimize these costs. For this, a mathematical simulation of the influence of climatic factors on the changes in materials parameters is necessary, which can be implemented based on mathematical models.

Printed devices based on microstrip lines are used for various purposes in REE, including REE protection against various interferences. In this respect, an important task is to analyze the influence of the climatic environment on the protective properties of devices, since they have a complicated configuration and a change in parameters can lead to a significant change in their characteristics.

For definiteness, we note the study of protective printed devices. For example, ultrashort pulses of the nano- and picosecond ranges present the greatest danger for REE, and therefore it is worth noting protection devices against ultrashort pulses based on meander line structures [3]. Their merit is the absence of a number of disadvantages of traditional solutions (for example, RLC-filters): low power and speed [4], influence of parasitic parameters [5], loss of properties of insulating dielectric between the capacitor plates [6]. There are also well-known studies of other protection devices based on printed structures and signal filtering in the frequency band widely pursued nowadays [7–12].

However, before analyzing complicated devices, it is advisable to practice an analysis approach and study simpler structures. A microstrip line is seen appropriate for this, and the first step for implementing climate models is the simplest one – the temperature model.

The aim of this paper is to carry out a study of the temperature effect on characteristics of a single microstrip line. To achieve this aim, it is necessary to introduce a mathematical temperature model; to calculate per-unit-length capacities and secondary parameters of the microstrip line with taking into account the environment temperature changes; and to analyze the results. In this work the simulation was performed using the TALGAT system [13], which implements the calculation of

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transmission line parameter matrices with the method of moments.

III. THEORY

The temperature model has the general view $P(T)$, where P is any of the structure characteristics, and T is the current temperature of external environment. The following parameter values of a microstrip line where was chosen as an initial one (Fig. 1): the width (w) and thickness (t) of the conductor were 1000 µm and 18 µm respectively, the PCB substrate thickness (h) was 500 µm, the distance from the structure edge to the signal conductor (d) was $3w$, the relative dielectric permittivity of the PCB substrate (ε_r) was 4.4.

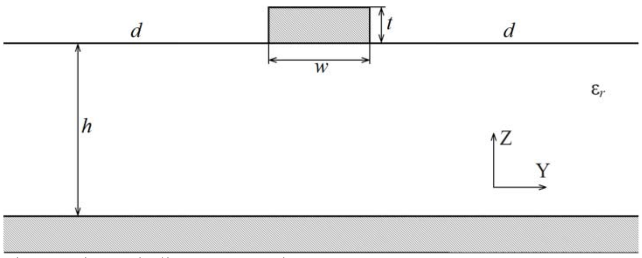

Fig. 1. Microstrip line cross-section.

In the TALGAT_Script software language, the thermal expansion model of each of the line parameters according to the well-known expression is implemented as following:

$$x=x_0(1+\alpha\Delta T) \quad (1)$$

where x is the value of line parameter according to thermal expansion; x_0 is the initial value of this parameter; α is the material linear thermal expansion coefficient; ΔT is the temperature difference. The temperature band was from minus 50 °C to 150 °C with the step of 25°C. The temperature difference was calculated from 25 °C. The value of α for copper was taken equal to $17\cdot10^{-6}$ according to [14] and for the PCB substrate along Z- and Y-axes was $70\cdot10^{-6}$ and $17\cdot10^{-6}$, respectively [15].

The temperature dependence of the ε_r was taken into account in a similar way. The coefficient α was obtained as follows. Based on the data from [16], the absolute coefficient of variation of ε_r from T was calculated as

$$\alpha_0 = \frac{\varepsilon_{rmax} - \varepsilon_{rmin}}{T_{max} - T_{min}} \quad (2)$$

where T_{max} and T_{min} are the maximum and minimum of the temperature range values, and ε_{rmax} and ε_{rmin} are the maximum and minimum of the relative dielectric permittivity values for the extreme points of the T range. Fig. 2 shows the dependence of ε_r from T with frequency changing, from which it follows that $\alpha_0=-0.003$. Then, dividing α_0 by the average ε_r value of 5.6 we obtain $\alpha=-5.35\cdot10^{-4}$.

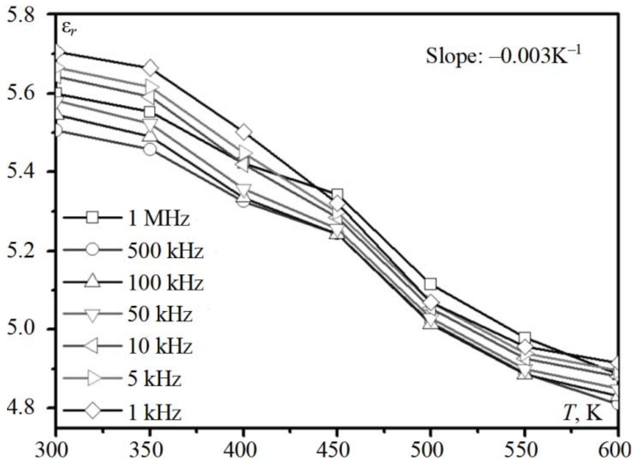

Fig. 2. Dependence $\varepsilon_r(T)$ for different frequencies from [16].

IV. RESULTS

The per-unit-length capacitance of the line with the dielectric (C) and in the air (C_0) was calculated taking into account the influence of temperature according to expression (1). The secondary parameters of the line – per-unit-length delay (τ) and characteristic wave impedance (Z) - were calculated additionally. Fig. 3 shows the obtained dependences on T for each of the cross-section parameters (w, t, h, d and ε_r) separately and simultaneously.

From the dependences, when the temperature separately affects each of the parameters, it can be seen that its effect on t and d practically does not lead to a change in C, C_0, τ and Z, and its effect on w leads to their insignificant changing. Thus, the maximum change of $C(T)$ was 0.22%, $C_0(T)$ – 0.18%, $\tau(T)$ – 0.017%, $Z(T)$ – 0.2%. The change in h has a greater effect on per-unit-length parameters. This is because the coefficient of linear thermal expansion for the substrate along the Z axis has a higher value. Thus, due to the influence of temperature only on h, the maximum change of $C(T)$ was already 0.93%, $C_0(T)$ – 0.79%, $\tau(T)$ – 0.07%, $Z(T)$ – 0.86%. Finally, the change in ε_r has the major effect on per-unit-length parameters. Obviously, this is due to the large value of α and its significant effect on the per-unit-length capacitance of the structure. Thus, because of the temperature influence only on ε_r, the maximum changes in $C(T)$, $\tau(T)$, and $Z(T)$ were 9.99%, 4.87%, and 4.88%, respectively. It is noteworthy that the obtained dependences have a different slope. For instance, from the presented results it can be seen that the effect of temperature on w and h differently affects the behavior of $C(T)$, $C_0(T)$, $\tau(T)$ and $Z(T)$. However, these dependences with the simultaneous influence of T on all parameters of the cross-section have a maximum slope, which is generally determined by the influence of ε_r. For example, with the simultaneous influence of T on all parameters of

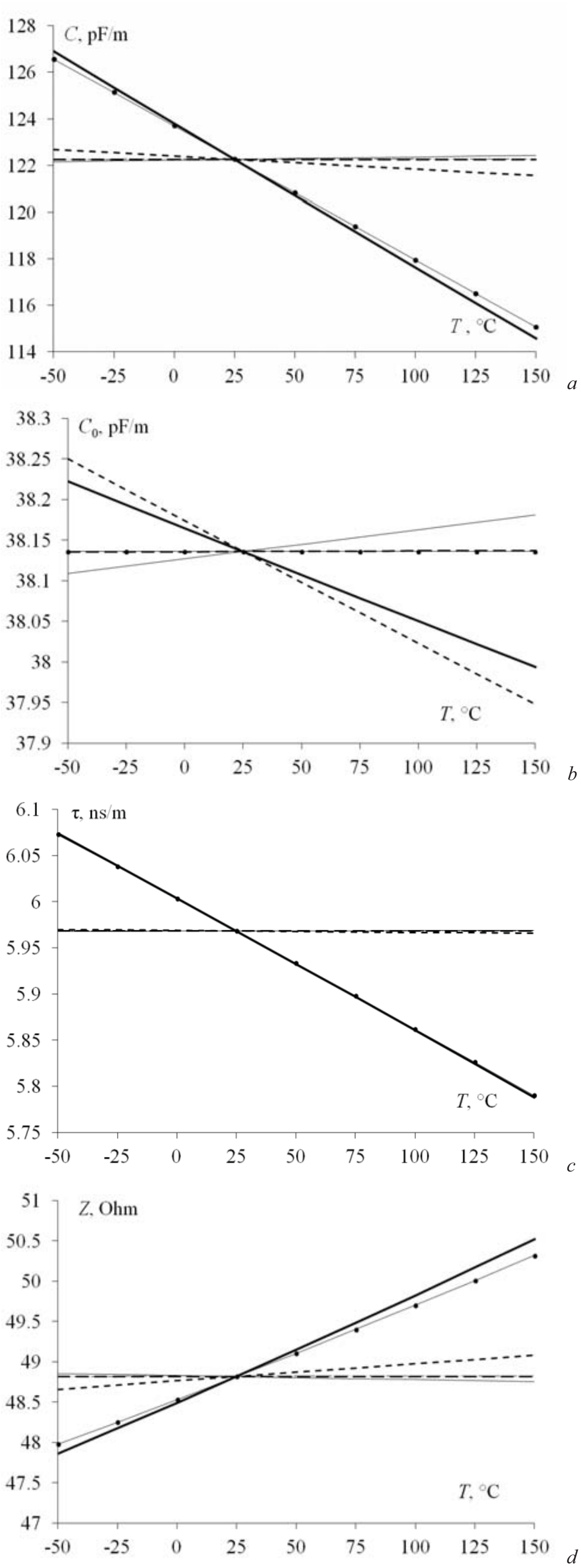

Fig. 3. $C(T)$, $C_0(T)$, $\tau(T)$ and $Z(T)$ (*a*–*d*) dependences under the influence of temperature on *w* (—), *t* (– –), *h* (- -), *d* (–·–) and ε_r (–•–) separately and simultaneously (▬).

the cross-section, the maximum change of $C(T)$ was already 10.76%, $C_0(T)$ – 0.6%, $\tau(T)$ – 4.93% and $Z(T)$ – 5.56%. The identical character of $C(T)$ and $C_0(T)$, $\tau(T)$ dependences and the opposite character of $Z(T)$ dependence are remarkable. The last can be easily explained by the expressions for calculating τ and *Z*:

$$\tau = \frac{(C/C_0)^{0.5}}{v_0},\ Z = \frac{1}{(v_0(CC_0)^{0.5})} \quad (3)$$

where v_0 is the speed of light in vacuum.

As it can be seen from expression (3), τ is directly proportional to *C* and inversely proportional to C_0, and since $C(T)$ and $C_0(T)$ have the same slope, then the slope of $\tau(T)$ coincides with the slope of $C(T)$ and $C_0(T)$. As it can be noted from expression (4), *Z* is inversely proportional to the product of *C* and C_0; therefore, $Z(T)$ dependence changes its slope as opposed to $C(T)$, $C_0(T)$ and $\tau(T)$. Thus, the separate influence of *T* on *w*, *t*, *h* and *d* in a rather wide range slightly changes the per-unit-length parameters of the line under investigation, while the maximum change of *C*, C_0, τ and *Z* does not exceed 1% when *T* changes in the range of minus 50 to 150°C. However, the separate influence of *T* on ε_r is significant and the maximum change of *C*, *τ* and *Z* is already 10%. With the simultaneous influence of *T* on the change of all structure parameters, the change in per-unit-length parameters is even higher and equals 10.76%. For clarity, Table 1 summarizes the calculated values of *w*, *t*, *h*, *d* and ε_r in the temperature range.

TABLE I
DEPENDENCE OF TRANSMISSION LINE PARAMETERS ON TEMPERATURE

T, °C	*w*, μm	*t*, μm	*h*, μm	*d*, μm	ε_r
–50	998.725	17.9771	497.375	2996.17	4.57655
–25	999.15	17.9847	498.25	2997.45	4.5177
0	999.575	17.9924	499.125	2998.72	4.45885
25	1000	18	500	3000	4.4
50	1000.42	18.0077	500.875	3001.27	4.34115
75	1000.85	18.0153	501.75	3002.55	4.2823
100	1001.28	18.023	502.625	3003.82	4.22345
125	1001.7	18.0306	503.5	3005.1	4.1646
150	1002.13	18.0382	504.375	3006.38	4.10575

V. CONCLUSION

A mathematical temperature model is presented and its study is performed on the example of a single microstrip line. It was revealed that the influence of temperature both separately on each of the cross-section parameters and together on all line parameters in a rather wide range has a significant effect on the per-unit-length capacitance and secondary parameters of the line under investigation. The maximum change of per-unit-length capacitances and secondary parameters of the line with a separate influence of temperature changes in the range from minus 50 to 150°C on each of the cross-section parameters of the line is 10%, and with a simultaneous influence on all parameters it is 10.76%. This effect is determined more by the influence of temperature on changing the relative permittivity. Thus, taking into account the described model, a significant effect of temperature on the per-unit-length characteristics was revealed.

However, for real materials, the coefficients of linear thermal expansion and changes of the relative permittivity caused by temperature may differ from the coefficients used in the presented model, which will affect the per-unit-length capacitance and secondary parameters of devices based on microstrip lines. In addition, in this paper we took only one set of parameter values. Meanwhile, the sensitivity of various characteristics to the changing of various parameters changes when their values change [17]. Therefore, it is possible to consider this. Thus, when designing such devices, it is important to take into account the temperature conditions in which they will be used and to perform the detailed simulation of them considering the temperature of the environment, as well as optimization, to achieve their required characteristics in the given temperature conditions.

The presented temperature model can be used for more complex structures. Therefore, the next step is to evaluate the effect of temperature changing, for example, on meander delay lines, described in detail in [3]. In addition, it is advisable to develop a mathematical model of the dependence of parameters on air humidity, since its influence can be significant. At the same time, it may be useful to consider the influence of these factors on the frequency characteristics of the structures. Finally, it is important to conduct field experiments and compare the results of measurements and simulations.

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