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Verification of Computer Simulation of Temperature Influence on Microstrip Line Characteristics

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***Abstract*—In this paper, we verify computer simulations of the influence of temperature (T) on the characteristics of a single microstrip line (MSL). Verification was conducted using two programs: MATLAB and TALGAT. A temperature model employed is based on the thermal coefficient that determines thermal changes in printed circuit boards (PCBs) of radio electronic equipment (REE). FR-4 glass epoxy laminate was chosen as the base dielectric material because of its widespread use as the substrate for PCBs, cost-effectiveness, and reliability (it has high glass transition temperature (Tg)). Ordinary copper was selected as the conductor material. Verification of computer simulation the impact of T (–50, 25, 150 °C) was performed with variations in parameters affecting the sensitivity (stability) of the characteristics of the MSL, namely propagation delay (τ) and characteristic impedance (Z). As a result, consistency of results was achieved for both characteristics τ and Z at all T values. The maximum difference was approximately 2.5%.**

***Keywords*—microstrip line, per-unit-length delay, printed circuit board, impedance, temperature, thermal coefficient**

I. INTRODUCTION

It is known that one of the destabilizing factors affecting the performance of radio electronic equipment (REE) is the ambient temperature (*T*) [1]. Therefore, when designing any REE PCBs, it is important to consider not only their construction but also the materials used as the base of the PCB and signal traces, as materials can impact the performance and cost of the final solution [2]. Therefore, when choosing the base material for PCBs, it is necessary, first of all, to pay attention to the stability of dimensions and the thermal coefficient (TC), denoted as α [3] and *Tg* (glass transition temperature), respectively.

Dimensional stability of PCBs is crucial for the quality of the manufactured products [4]. Therefore, it is essential to consider potential changes in dimensions that can occur in the production process during the design stage. To prevent component shifting and maintain the accuracy of mounting locations, it is essential to use materials with high stability. This is particularly important when dealing with large batches of products.

Additionally, in the production of electronic components for REE, α is crucial, as it determines material changes in size or properties with variations in *T*. Inconsistency in α with the intended operating and production conditions can cause PCB deformation (bending) and tension in solder joints, which inevitably reduces device reliability and potentially causes operational failures [5]. This can be particularly critical for electronic components of REE, where even minor deformations can disrupt operation or damage components. However, α is a variable quantity [6] and depends on another parameter, *Tg*, which determines the threshold of *T*. When this threshold is exceeded, the PCB begins to exhibit plasticity to some extent, and noticeable expansion occurs. In this regard, for some materials, α may change upon exceeding *Tg*. Due to this, the PCB significantly expands upon surpassing *Tg*. The higher the *Tg*, the less deformation occurs, thus increasing the reliability of the PCB. Otherwise, expansion can lead to breakage or track closure, as α of copper differs from that of the glass epoxy laminate. In simpler terms, the low plasticity of copper is insufficient to resist the force exerted by the expanding PCB.

Therefore, prior to the production of PCBs for operating under harsh environmental conditions, particularly at low and high temperatures, for example, from the Arctic to space, accurate computer simulation is crucial [7]. It allows for reducing material costs and increasing reliability before production. In this regard, it is essential to consider a temperature model during simulation, which enables an assessment of the temperature influence on the characteristics of transmission lines (TL) of REE PCBs. The most commonly implemented transmission line on PCBs is the microstrip line (MSL) [8]. The effects of temperature on its characteristics have been previously investigated through computer simulation [9]. However, to provide the reliability of the simulation results before production, it is important to perform their verification using various computer programs or automated design systems. The programs include PCB Toolkit V7.05, AppCAD, FasterCap, Rogers Corporation MWI Calculator developed by Saturn PCB Design, Inc. They allow simulating thermal conductivity and calculating TL characteristics. However, they do not account for the influence of temperature on the characteristics. Meanwhile, this capability is provided by the Electromagnetic Compatibility Modeling System TALGAT [10] developed at the Fundamental Research Laboratory for Electromagnetic Compatibility, where the authors of this paper work. Thus, the aim of this study is to verify the results of computer simulation of temperature influence using the characteristics of a single MSL as an example.

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II. INITIAL DATA

The verification of temperature influence simulation was conducted using the temperature model with the MATLAB R2023a software. MATLAB R2023a offers capabilities for modeling various transmission lines (TL), including the RF Toolbox package and Transmission Line Designer applications. Importantly, it allows for the direct integration of the temperature model into the code using fragments [11]. It is worth noting that both TALGAT and MATLAB are based on the Method of Moments (MoM), ensuring consistency in the approach to simulation.

Figure 1 shows the cross-sectional views constructed in MATLAB and TALGAT. The parameters of the cross-section remain constant: conductor thickness t=70 µm, distance from the edge to the conductor d=3.5 mm, and relative dielectric permittivity ε_r=4.5 (FR-4). The variable parameters are the width of the signal conductor w=0.3–1.5 mm with a step of 0.3 mm and the substrate thickness h=0.2–1 mm with a step of 0.1 mm.

To account for the effect of T, the following α along the axes were selected according to the technical documents for FR-4 [12, 13]: $\alpha(X)=14\cdot10^{-6}\text{K}^{-1}$, $\alpha(Y)=12\cdot10^{-6}\text{K}^{-1}$, $\alpha(Z)=70\cdot10^{-6}\text{K}^{-1}$ for T=–50 and 25 °C, and $\alpha(Z)=280\cdot10^{-6}\text{K}^{-1}$ for T=150 °C, since for FR-4 Tg=135 °C, $\alpha(\varepsilon_r)=14\cdot10^{-6}\text{K}^{-1}$. As a conductor material, we chose ordinary copper with $\alpha=17\cdot10^{-6}\text{K}^{-1}$ [14].

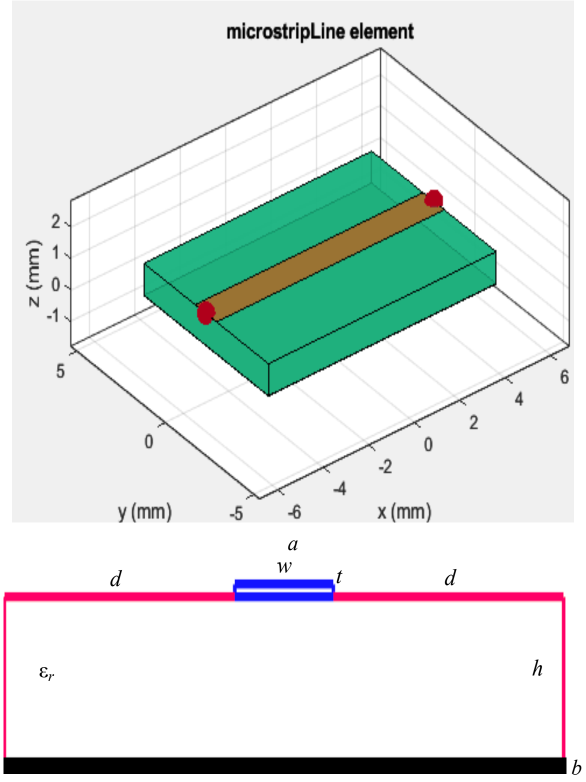


Fig. 1. The cross-sections of the microstrip transmission line (MTL) constructed in MATLAB (a) and TALGAT (b)

III. SIMULATION RESULTS

The dependencies of τ and characteristic impedance (Z) on h for w=0.3–1.5 mm with a step of 0.3 mm at T=–50, 25, and 150 ºC, calculated in MATLAB (Fig. 2) and in TALGAT, are presented in Fig. 3. We can see that the behavior of the dependencies is consistent across both programs. Specifically, with an increase in h, τ decreases while Z increases. Additionally, τ values increase with increasing w, where as Z values decrease.

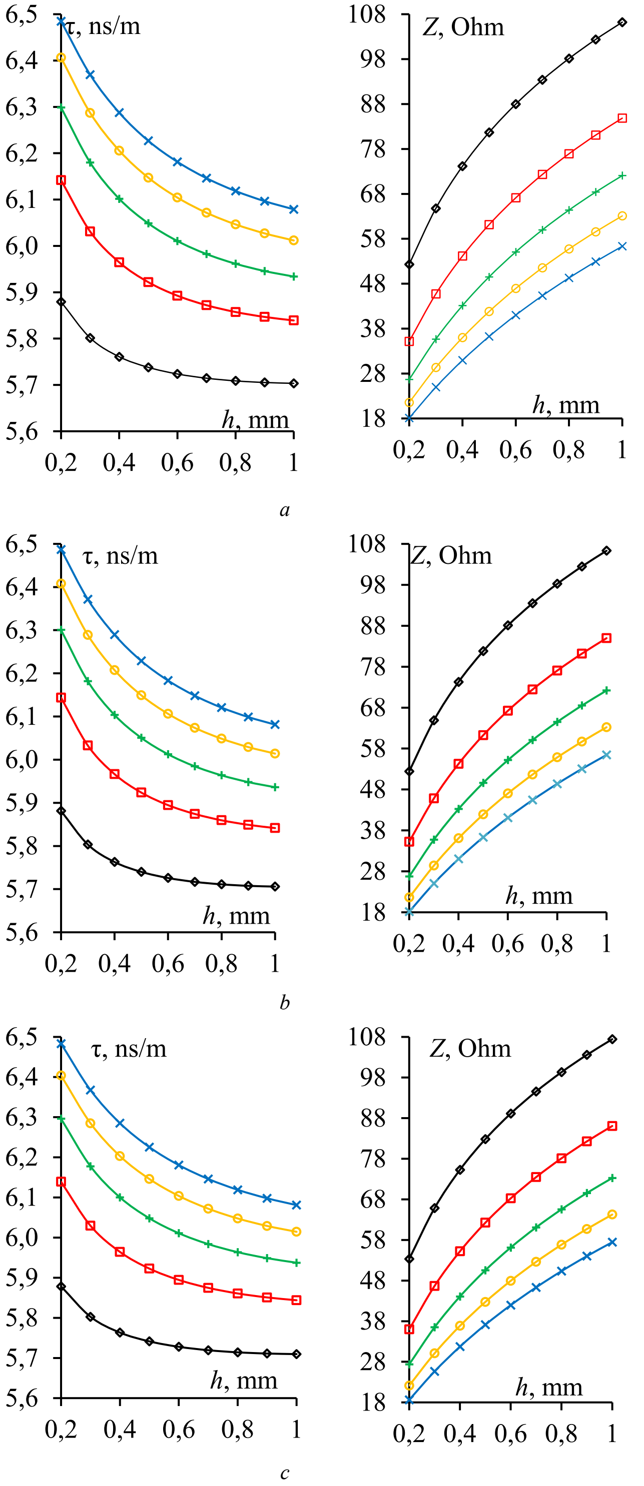
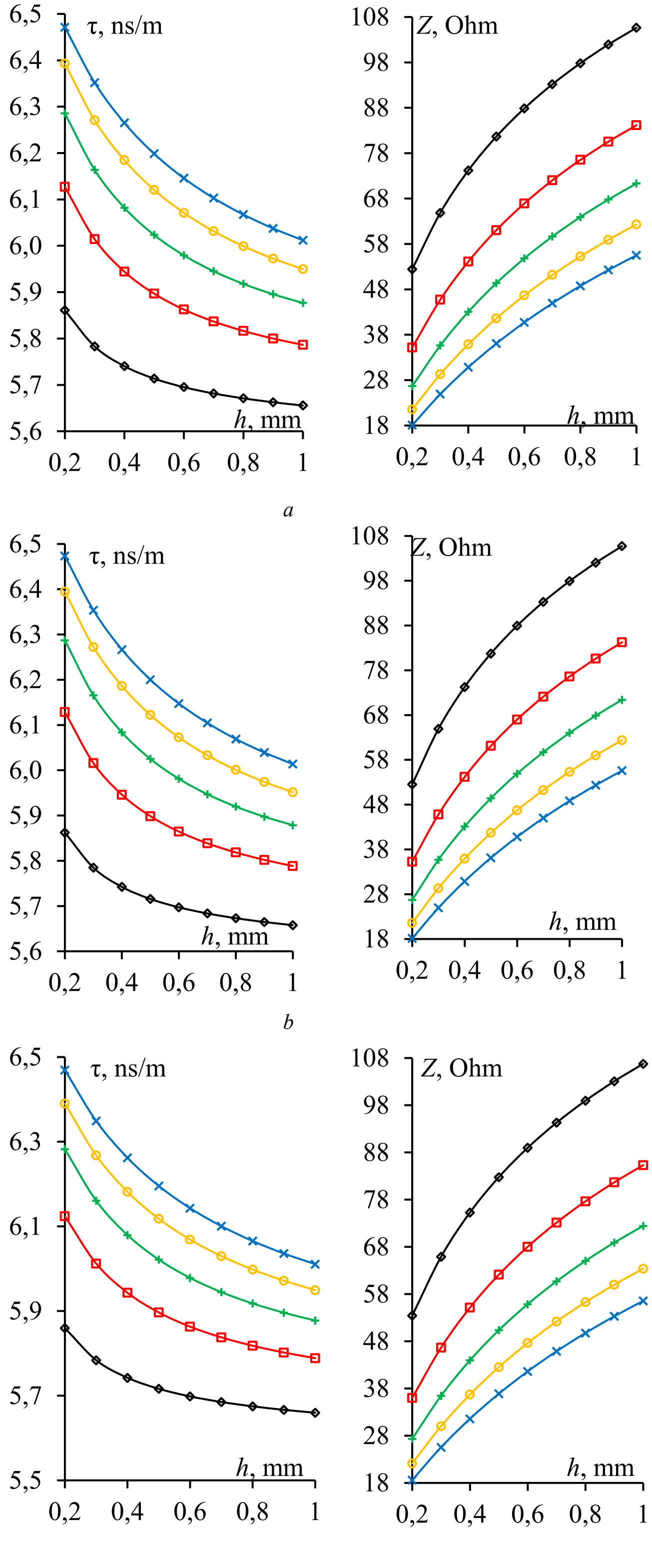


Fig. 2. Dependences of τ and Z on h at T=–50 (a), 25 (b), and 150 (c) ºC for w=0,3 (◊), 0,6 (□), 0,9 (+), 1,2 (○),1,5 (×) mm, calculated in MATLAB



a

b

c

Fig. 3. Dependences of τ and *Z* on *h* at *T*=–50 (*a*), 25 (*b*), and 150 (*c*) ºC for *w*=0,3 (◊), 0,6 (□), 0,9 (+), 1,2 (○),1,5 (×) mm, calculated in TALGAT

For a more precise comparison, the dependencies of τ and *Z* are separately presented for the extreme values of *w*=0.3 and 1.5 mm across the entire range of *h* at *T*=25 ºC (Fig. 4). It can be seen that the dependencies of τ slightly differ with increasing *h* for the two programs, while *Z* remains almost identical.

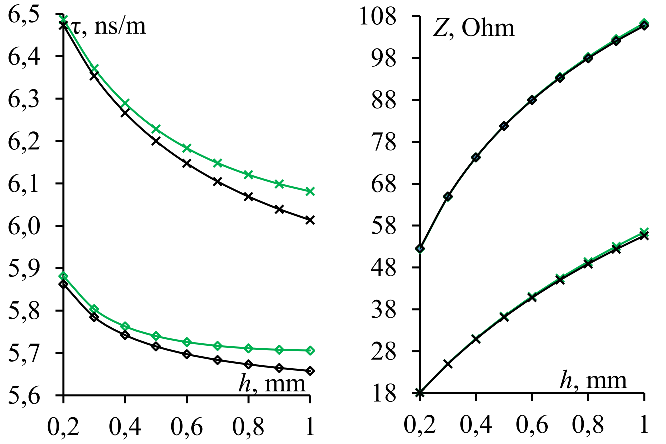


Fig. 4. Dependences of τ and *Z* on *h* at *T*=25 ºC for *w*=0,3 (◊) and 1,5 (×) mm, calculated in MATLAB (green) and in TALGAT (black)

The relative deviations of τ and *Z* between the two programs were computed for all *T* values and are presented in Tables I and II, respectively. We can see that they are very small. For instance, the maximum deviations (at *w*=1.5 mm, *h*=1 mm, and *T*=150 ºC) are 1.167% for τ and 1.574% for *Z*.

TABLE I. RELATIVE MODULE (%) OF DEVIATIONS IN τ BETWEEN TWO PROGRAMS

***h*, mm**	***T*, ºC**	***w*, mm**				
		0,3	**0,6**	**0,9**	**1,2**	**1,5**
0,2	–50	0,317	0,244	0,212	0,209	0,209
	25	0,318	0,246	0,214	0,207	0,210
	150	0,316	0,247	0,217	0,211	0,216
0,3	–50	0,320	0,280	0,265	0,264	0,279
	25	0,322	0,281	0,266	0,265	0,280
	150	0,327	0,287	0,274	0,276	0,291
0,4	–50	0,355	0,342	0,325	0,340	0,361
	25	0,357	0,344	0,327	0,341	0,364
	150	0,364	0,354	0,339	0,345	0,369
0,5	–50	0,426	0,424	0,421	0,437	0,457
	25	0,427	0,426	0,423	0,439	0,461
	150	0,438	0,441	0,440	0,457	0,481
0,6	–50	0,501	0,512	0,522	0,549	0,582
	25	0,502	0,515	0,525	0,553	0,584
	150	0,518	0,534	0,545	0,576	0,610
0,7	–50	0,581	0,606	0,627	0,666	0,710
	25	0,584	0,610	0,631	0,671	0,715
	150	0,603	0,632	0,657	0,700	0,746
0,8	–50	0,666	0,704	0,739	0,789	0,843
	25	0,670	0,707	0,743	0,795	0,849
	150	0,691	0,734	0,774	0,828	0,885
0,9	–50	0,754	0,806	0,853	0,915	0,979
	25	0,758	0,811	0,859	0,919	0,985
	150	0,785	0,842	0,894	0,959	1,027
1	–50	0,847	0,912	0,971	1,042	1,115
	25	0,852	0,917	0,976	1,048	1,123
	150	0,882	0,953	1,016	1,091	1,167

TABLE II. RELATIVE MODULE (%) OF DEVIATIONS IN *Z* BETWEEN TWO PROGRAMS

***h*, mm**	***T*, ºC**	***w*, mm**				
		0,3	**0,6**	**0,9**	**1,2**	**1,5**
0,2	–50	0,219	0,085	0,006	0,059	0,109
	25	0,219	0,084	0,007	0,064	0,111
	150	0,210	0,079	0,013	0,072	0,118
0,3	–50	0,115	0,014	0,112	0,205	0,266
	25	0,114	0,015	0,113	0,206	0,267
	150	0,107	0,023	0,122	0,217	0,279
0,4	–50	0,026	0,104	0,232	0,336	0,420
	25	0,025	0,106	0,234	0,338	0,423
	150	0,015	0,118	0,247	0,363	0,450
0,5	–50	0,045	0,194	0,338	0,467	0,580
	25	0,046	0,197	0,340	0,469	0,583
	150	0,060	0,214	0,360	0,492	0,608
0,6	–50	0,128	0,298	0,458	0,603	0,734
	25	0,130	0,301	0,461	0,607	0,738
	150	0,147	0,322	0,486	0,635	0,770
0,7	–50	0,220	0,413	0,590	0,753	0,901
	25	0,223	0,416	0,594	0,757	0,906
	150	0,248	0,447	0,629	0,796	0,949
0,8	–50	0,322	0,538	0,734	0,914	1,082
	25	0,326	0,542	0,739	0,920	1,088
	150	0,358	0,580	0,782	0,968	1,142
0,9	–50	0,436	0,675	0,892	1,091	1,278
	25	0,440	0,681	0,898	1,098	1,286
	150	0,479	0,727	0,950	1,157	1,351
1	–50	0,561	0,826	1,063	1,284	1,492
	25	0,566	0,832	1,071	1,292	1,501
	150	0,608	0,883	1,129	1,358	1,574

The relative deviation modules of the temperature influence on τ and *Z* characteristics calculated from the MATLAB and TALGAT data are presented in Tables III and IV, respectively. It can be seen that they are small when *T* increases or decreases. The maximum values for τ (at *w*=0.3 mm, *h*=1 mm, and *T*=150 ºC) are 0.067% (MATLAB) and 0.038% (TALGAT), and for *Z* (at *w*=1.5 mm, *h*=0.2 mm, and *T*=150 ºC), they are 2.577% (MATLAB) and 2.569% (TALGAT).

TABLE III. RELATIVE DEVIATION MODULES (%) FOR τ AND *Z* (MATLAB)

***h*, mm**	***T*, ºC**	***w*, mm**					
		Characteristics	**0,3**	**0,6**	**0,9**	**1,2**	**1,5**
0,2	–50	τ	0,031	0,029	0,030	0,028	0,032
		Z	0,178	0,224	0,249	0,269	0,277
	150	τ	0,046	0,075	0,073	0,066	0,055
		Z	1,739	2,133	2,346	2,482	2,577
0,3	–50	τ	0,034	0,030	0,029	0,030	0,030
		Z	0,152	0,198	0,225	0,243	0,256
	150	τ	0,012	0,055	0,066	0,065	0,061
		Z	1,516	1,910	2,144	2,299	2,410
0,4	–50	τ	0,036	0,032	0,031	0,029	0,032
		Z	0,135	0,179	0,207	0,226	0,241
	150	τ	0,009	0,035	0,054	0,069	0,070
		Z	1,375	1,747	1,987	2,163	2,286
0,5	–50	τ	0,037	0,034	0,031	0,031	0,032
		Z	0,123	0,164	0,192	0,213	0,228
	150	τ	0,024	0,017	0,040	0,050	0,053
		Z	1,277	1,624	1,863	2,035	2,165
0,6	–50	τ	0,038	0,036	0,033	0,033	0,031
		Z	0,114	0,153	0,180	0,201	0,217
	150	τ	0,037	0,002	0,027	0,039	0,044
		Z	1,203	1,526	1,760	1,934	2,069
0,7	–50	τ	0,040	0,037	0,035	0,035	0,034
		Z	0,107	0,144	0,170	0,191	0,207
	150	τ	0,045	0,010	0,012	0,026	0,034
		Z	1,151	1,453	1,679	1,853	1,990
0,8	–50	τ	0,042	0,038	0,037	0,036	0,036
		Z	0,102	0,136	0,162	0,183	0,199
	150	τ	0,053	0,022	0,000	0,015	0,025
		Z	1,109	1,393	1,611	1,783	1,921
0,9	–50	τ	0,002	0,003	0,003	0,003	0,004
		Z	0,098	0,130	0,155	0,176	0,192
	150	τ	0,061	0,032	0,012	0,002	0,013
		Z	1,075	1,345	1,554	1,723	1,862
1	–50	τ	0,044	0,041	0,039	0,038	0,038
		Z	0,095	0,126	0,150	0,170	0,186
	150	τ	0,067	0,041	0,022	0,007	0,005
		Z	1,045	1,302	1,503	1,668	1,806

TABLE IV. RELATIVE DEVIATION MODULES (%) FOR τ AND *Z* (TALGAT)

***h*, mm**	***T*, ºC**	***w*, mm**					
		Characteristics	**0,3**	**0,6**	**0,9**	**1,2**	**1,5**
0,2	–50	τ	0,030	0,028	0,029	0,030	0,032
		Z	0,178	0,224	0,248	0,264	0,275
	150	τ	0,044	0,076	0,076	0,070	0,061
		Z	1,730	2,127	2,340	2,475	2,569
0,3	–50	τ	0,033	0,029	0,028	0,029	0,030
		Z	0,151	0,197	0,224	0,242	0,255
	150	τ	0,017	0,061	0,074	0,076	0,073
		Z	1,510	1,902	2,134	2,288	2,398
0,4	–50	τ	0,035	0,030	0,029	0,028	0,029
		Z	0,134	0,178	0,206	0,225	0,239
	150	τ	0,001	0,045	0,066	0,074	0,075
		Z	1,365	1,735	1,973	2,137	2,258
0,5	–50	τ	0,036	0,032	0,029	0,029	0,028
		Z	0,121	0,162	0,190	0,210	0,225
	150	τ	0,013	0,032	0,056	0,069	0,074
		Z	1,263	1,606	1,843	2,012	2,139
0,6	–50	τ	0,037	0,033	0,030	0,029	0,029
		Z	0,112	0,150	0,177	0,197	0,213
	150	τ	0,021	0,021	0,047	0,062	0,070
		Z	1,186	1,505	1,735	1,906	2,037
0,7	–50	τ	0,038	0,034	0,031	0,030	0,029
		Z	0,105	0,140	0,166	0,187	0,202
	150	τ	0,027	0,012	0,038	0,055	0,065
		Z	1,125	1,423	1,644	1,814	1,947
0,8	–50	τ	0,038	0,035	0,032	0,030	0,029
		Z	0,099	0,132	0,157	0,177	0,193
	150	τ	0,034	0,001	0,023	0,041	0,054
		Z	1,077	1,355	1,567	1,734	1,867

***h*, mm**	***T*, °C**	***w*, mm**					
		Characteristics	**0,3**	**0,6**	**0,9**	**1,2**	**1,5**
0,9	–50	τ	0,038	0,035	0,033	0,031	0,030
		Z	0,094	0,125	0,149	0,169	0,184
	150	τ	0,034	0,001	0,023	0,041	0,054
		Z	1,036	1,298	1,501	1,664	1,797
1	–50	τ	0,039	0,036	0,033	0,032	0,030
		Z	0,090	0,119	0,142	0,161	0,177
	150	τ	0,037	0,006	0,018	0,036	0,049
		Z	1,002	1,250	1,444	1,603	1,733

IV. CONCLUSION

Thus, we have verified computer simulation results for the temperature influence (*T*) on the characteristics of a single microstrip line (MSL). The verification was carried out in MATLAB by quantitatively comparing the results obtained with our TALGAT program. The comparison results demonstrated that the data for both τ and *Z* characteristics are in good qualitative agreement. The maximum discrepancy was approximately 2.5%, confirming the accuracy of simulation in the TALGAT program.

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