Characteristic Parameters Determination of Different Striplines Configurations using HBEM

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Abstract **─** Different configurations of striplines are analyzed using the hybrid boundary element (HBEM) method, developed at the Faculty of Electronic Engineering of Niš. The quasi TEM analysis is applied. The effective dielectric permittivity as well as the characteristic impedance of several 2D striplines are determined. In order to validate the obtained HBEM values of the characteristic impedance, in terms of accuracy, they have been compared with the corresponding ones obtained by the finite element method. Fast convergence of the results, short computation time, and possibility to solve complex multi-layered configurations of striplines, make hybrid boundary element method very efficient in the calculation of 2D striplines parameters. All results are presented in tables and graphically.

Index Terms **─** Characteristic impedance, equivalent electrodes method, finite element method, hybrid boundary element method, and stripline.

I. INTRODUCTION

Stripline is a structure having a strip sandwiched in a dielectric layer between two ground planes [1]. Such structure can be used in printed-circuit boards, ground-signal-ground transmission lines, multilayer boards, as a part of an antenna power divider, etc. Analytical solutions for centered, off-centered, and shielded striplines are given in [1]. There is mentioned that a large number of authors [2, 3] describe such configurations. In order to calculate the characteristic impedances of the striplines, different analytical and numerical techniques are used: the conformal mapping [3], the finite element method (FEM) and the method of lines (MoL) [4], the Fourier transform method [5], the method of moments (MoM) [6], the integral equation techniques [7-10], the equivalent electrodes method (EEM) [11], the generalized spectral domain analysis, etc. The integral equation method is applied in [8] for computing the capacitance and inductance matrix for a multiconductor transmission line in a multilayer dielectric region. Characteristic parameters of the stripline, placed in an anisotropic media between two ground planes, are analyzed in [11].

The purpose of this paper is to present some other configurations of striplines placed in the multilayer media and to verify the accuracy of the hybrid boundary element method [12]. This method, developed at our Department, is a combination of the equivalent electrodes method [13] and the boundary element method (BEM) [14, 15]. The EEM, which resembles the MoM [16], but is however very different from it, was successfully applied in [17-19] for solving the problems with multilayer media, as well as the problems of transmission and shielded slot lines. Generally, the application of the EEM depends on the Green's function of the observed problem, and therefore the method is based on the combination of analytical derivation of the Green's function in the closed form and the numerical procedure for solving simplified problems. In some cases, finding the Green's function in the closed form can be very difficult or even impossible. It is very important to notice that the EEM application does not require any kind of numerical integration for problem solving. In the MoM, the numerical integration is always present. That produces some prob-

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lems in the numerical solving of non-elementary integrals having singular subintegral functions.

An improvement of the EEM has been achieved combining it with the BEM, in order to solve problems of arbitrarily shaped multilayer structures, where finding the Green's function can be very difficult or even impossible. That method is called the hybrid boundary element method (HBEM). It is based on the EEM, on the point-matching method (PMM) for the potential of the perfect electric conductor (PEC) electrodes and for the normal component of the electric field at the boundary surface between any two dielectric layers.

Until now, the method is applied to solving multilayer electromagnetic problems [12], grounding systems [20], as well as electromagnetic field determination in the vicinity of cable terminations [21]. The HBEM can be successfully applied to analysis of corona effects [22] and metamaterial structures [23]. This method can be also used to the 3D problems solving that will be presented in future papers. Through the several examples, the HBEM is applied to determine both the effective dielectric permittivity and the characteristic impedance. A computer code has been written to obtain numerical solutions for those examples of 2D striplines. The main assumption of the analysis involves quasi TEM propagation in investigated striplines. In order to test the accuracy of the developed method, the numerical results are presented for all presented examples and compared with those obtained by FEM, [24].

The theoretical approach is presented in section II. Section III is devoted to show that highly accurate results can be obtained with short computation time. Also, the obtained numerical results are given in this section. The conclusions are summarized in section IV.

II. THEORETICAL APPROACH

A cross-section of the stripline sandwiched in multilayer dielectric between two ground planes is shown in Fig. 1. According to the HBEM, an arbitrary shaped electrode can be replaced by the equivalent electrodes, and an arbitrary shaped boundary surface between any two dielectric layers can be replaced by discrete equivalent total line charges placed in the air, as seen in Fig. 2. The discretization technique is similar to the method of moments and is well known.

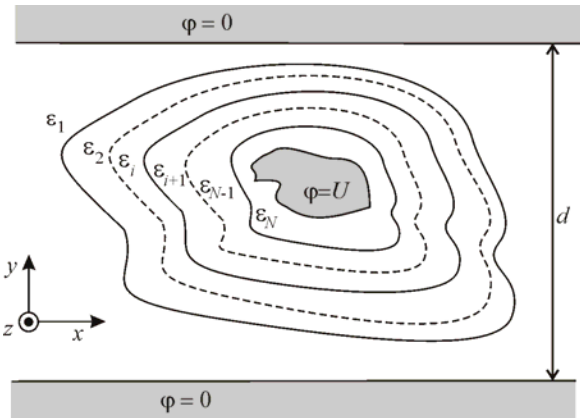

Fig. 1. Stripline in multilayer dielectric.

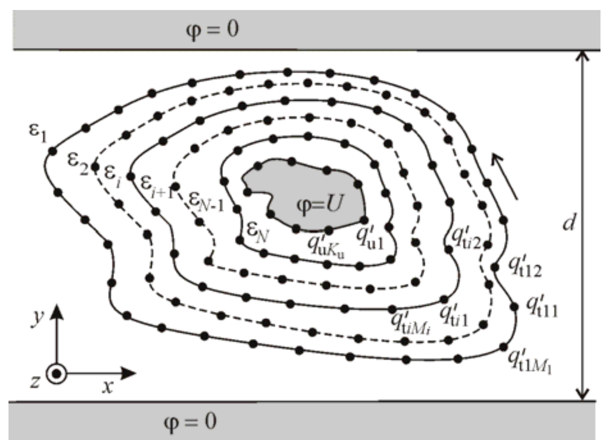

Fig. 2. Corresponding HBEM model.

Since the free surface charges do not exist on dielectric boundary surfaces (free surface charges exist only on PEC, see Fig. 2), the total surface charges between the dielectric layers are equal to the polarized surface charges. The Green's function of the line charge placed at height h, parallel to two infinite parallel ground planes is, [25],

$$G(x,y)=\frac{1}{2\pi\varepsilon}\ln\sqrt{\frac{\cosh\left[\frac{\pi}{d}x\right]-\cos\left[\frac{\pi}{d}(y+h)\right]}{\cosh\left[\frac{\pi}{d}x\right]-\cos\left[\frac{\pi}{d}(y-h)\right]}} \tag{1}$$

where d is the distance between two planes. Using this Green's function, the electric scalar potential of the observed system from Fig. 2 is,

$$\varphi=\sum_{k=1}^{K_u}\frac{q'_{uk}}{2\pi\varepsilon_N}\ln\sqrt{\frac{\cosh\left[\frac{\pi}{d}(x-x_{uk})\right]-\cos\left[\frac{\pi}{d}(y+y_{uk})\right]}{\cosh\left[\frac{\pi}{d}(x-x_{uk})\right]-\cos\left[\frac{\pi}{d}(y-y_{uk})\right]}}+$$
$$+\sum_{i=1}^{N-1}\sum_{m=1}^{M_i}\frac{q'_{tim}}{2\pi\varepsilon_0}\ln\sqrt{\frac{\cosh\left[\frac{\pi}{d}(x-x_{tim})\right]-\cos\left[\frac{\pi}{d}(y+y_{tim})\right]}{\cosh\left[\frac{\pi}{d}(x-x_{tim})\right]-\cos\left[\frac{\pi}{d}(y-y_{tim})\right]}},$$
$$N\geq 2, \qquad (2)$$

and the electric field is $\boldsymbol{E}=-\mathrm{grad}(\varphi)$, where: M_i is the number of equivalent electrodes (EEs) on the i-th boundary surface between two layers. In the following examples, the total number of unknowns N_{tot}, will be denoted by,

$$N_{\mathrm{tot}}=K_u+\sum_{i=1}^{N-1}M_i\,.$$

A relation between the normal component of the electric field and total surface charges is presented as,

$$\hat{\boldsymbol{n}}_{im}\cdot\boldsymbol{E}_{im}^{(0+)}=\frac{-\varepsilon_{i+1}}{\varepsilon_0(\varepsilon_i-\varepsilon_{i+1})}\eta_{tim},$$
$$\eta_{tim}=\frac{q'_{tim}}{\Delta l_{im}},\ m=1,\ldots,M_i,\ i=1,\ldots,N-1, \qquad (3)$$

where $\hat{\boldsymbol{n}}_{im}$ is the unit normal vector oriented from the layer ε_{i+1} towards the layer ε_i. Positions of the matching points for the potential of the PEC are,

$$x_{un}=x_{uk}+\delta_{nk}a_{euk}\hat{\mathbf{n}}_{uk}\cdot\hat{\mathbf{x}}$$
$$y_{un}=y_{uk}+\delta_{nk}a_{euk}\hat{\mathbf{n}}_{uk}\cdot\hat{\boldsymbol{y}},$$
$n=1,\ldots,K_u$, $k=1,\ldots,K_u$ and $a_{euk}=\Delta l_{uk}/4$,

where δ_{nk} is the Kronecker's delta function,

$$\delta_{nk}=\begin{cases}1, & n=k\\ 0, & n\neq k,\end{cases} \qquad (4)$$

while a_{euk} are corresponding to the EEs radii.

Boundary surface matching points for the normal component of the electric field on the i-th boundary surface are,

$$x_{tin}=x_{tim}+\delta_{nm}a_{eim}\hat{\boldsymbol{n}}_{im}\cdot\hat{\boldsymbol{x}}\ \text{and}$$
$$y_{tin}=y_{tim}+\delta_{nm}a_{eim}\hat{\boldsymbol{n}}_{im}\cdot\hat{\boldsymbol{y}},$$

$i=1,\ldots,N-1$, $n=1,\ldots,M_i$ and $m=1,\ldots,M_i$, where $a_{eim}=\Delta l_{im}/\pi$ are the EEs radii.

The aim is to obtain the quadratic system of linear equations with unknown free charges of PEC and total charges per unit length at the boundary surfaces between dielectric layers. Using the PMM for the potential of the conductor given by equation (2) and the PMM for the normal component of the electric field given in equation (3), it is possible to determine unknown charges. After solving the system of linear equations it is possible to calculate the capacitance per unit length of the stripline,

$$C'=\sum_{k=1}^{K_u}\frac{q'_{uk}}{U}. \qquad (5)$$

The characteristic impedance of the stripline is calculated as $Z_c=Z_{c0}\big/\sqrt{\varepsilon_r^{\mathrm{eff}}}$, where $\varepsilon_r^{\mathrm{eff}}=C'/C'_0$ is the effective dielectric permittivity, and Z_{c0} is the characteristic impedance of the stripline without dielectrics (free space). In order to compare the obtained results for the characteristic impedance, the FEM, [24], is used. A deviation between the HBEM and FEM results will be defined as,

$$\delta[\%]=\frac{\left|Z_c^{\mathrm{HBEM}}-Z_c^{\mathrm{FEM}}\right|}{Z_c^{\mathrm{FEM}}}\cdot 100. \qquad (6)$$

III. NUMERICAL RESULTS AND DISCUSSION

A. Example 1

The geometry of the stripline with a circular cross-section is shown in Fig. 3. After applying the HBEM using the procedure described in section II, the unknown free charges per unit length of the conductor and the total charges per unit length on the boundary surfaces between layers are calculated.

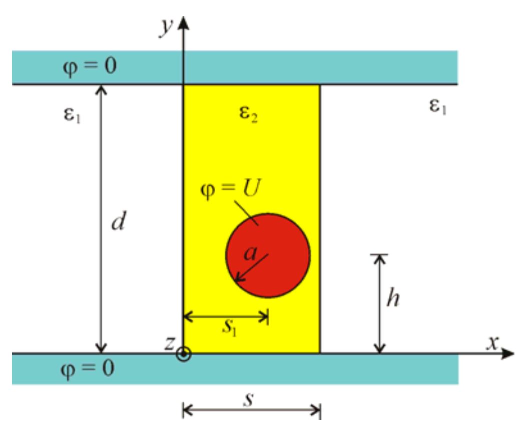

Fig. 3. Stripline with circular cross-section.

Two characteristic parameters of the stripline are determined: the effective dielectric permittivity and the characteristic impedance. Values of these two parameters and the computation time are calculated for: $\varepsilon_{r1} = 1$, $\varepsilon_{r2} = 3$, $s/d = 0.5$, $s_1/s = 0.6$, $h/d = 0.4$, and $a/s = 0.3$ and presented in Table I. N_{tot} is the total number of unknown values.

Table I: Convergence of the results and computation time.

N_{tot}	ε_r^{eff}	Z_c [Ω]	t(s)
247	2.2820	54.741	7.7
329	2.2828	54.831	13.6
413	2.2832	54.885	21.2
494	2.2835	54.918	30.6
576	2.2837	54.944	41.9
660	2.2838	54.963	54.9
741	2.2840	54.977	69.0
823	2.2841	54.989	85.3
988	2.2842	55.006	122.0
1070	2.2843	55.013	144.4
1154	2.2843	55.019	167.8

The calculation was performed on the computer with dual core INTEL processor 2.8 GHz and 4 GB of RAM. Analyzing Table I, following conclusions can be given. First, a very good convergence of values of both parameters is achieved. Increasing the number of unknown, the computation time increases linearly. The computation time is very short. For the system of 1154 unknowns we needed up to 167.8 seconds.

Equipotential contours and the normalized distribution of the polarized charges per unit length along the boundary surfaces are shown in Figs. 4 and 5, respectively for: $\varepsilon_{r1} = 1$, $\varepsilon_{r2} = 3$, $s/d = 0.5$, $s_1/s = 0.6$, $h/d = 0.4$, and $a/s = 0.3$. In order to validate the accuracy of the HBEM results for the effective dielectric permittivity and characteristic impedance of the stripline, the comparison of those values obtained by HBEM and FEM versus s_1/s and h/d for $\varepsilon_{r1} = 1$, $\varepsilon_{r2} = 3$, $s/d = 0.5$, and $a/s = 0.3$, is presented in Table II. The table shows that the numerical results for the effective dielectric permittivity and the characteristic impedance obtained using the HBEM are obviously in very good agreement with the FEM values with divergence less than 0.55 %.

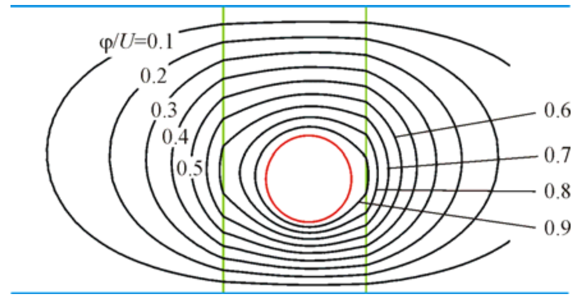

Fig. 4. Equipotential contours.

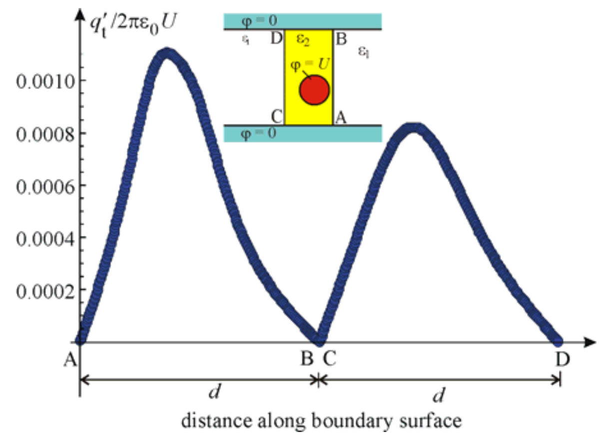

Fig. 5. Distribution of polarized charges per unit length along the boundary surfaces.

Table II: Comparison between the values of dielectric permittivity and characteristic impedance of the stripline versus s_1/s and h/d for: $\varepsilon_{r1} = 1$, $\varepsilon_{r2} = 3$, $s/d = 0.5$, and $a/s = 0.3$.

$\frac{s_1}{s}$	$\frac{h}{d}$	HBEM		FEM	
		ε_r^{eff}	Z_c [Ω]	ε_r^{eff}	Z_c [Ω]
0.35	0.2	2.5844	28.361	2.5837	28.517
	0.3	2.3532	46.713	2.3540	46.792
	0.4	2.2566	55.293	2.2577	55.349
	0.5	2.2285	57.923	2.2296	57.977
0.4	0.2	2.6183	28.176	2.6177	28.331
	0.3	2.3850	46.401	2.3857	46.480
	0.4	2.2838	54.963	2.2849	55.018
	0.5	2.2542	57.596	2.2554	57.645
0.5	0.2	2.6446	28.036	2.6441	28.190
	0.3	2.4100	46.154	2.4113	46.233
	0.4	2.3059	54.699	2.3070	54.754
	0.5	2.2751	57.332	2.2762	57.380

Increasing the parameter h/d to the center distance between the parallel planes ($h/d = 0.5$), the characteristic impedance increases too. After that value ($h/d > 0.5$), the characteristic impedance decreases. Those higher values are the same distances as for $h/d < 0.5$, but this time from the upper plane. An influence of the circular conductor radius on the characteristic impedance and the effective dielectric permittivity is presented in Table III. The HBEM results are compared with the corresponding FEM results. The results deviation is presented in Table III as well. This deviation parameter indicates a good results agreement between both methods.

Table III: Comparison between the values of dielectric permittivity and characteristic impedance of the stripline versus a/s for: $\varepsilon_{r1} = 1$, $\varepsilon_{r2} = 3$, $s/d = 0.5$, $s_1/s = 0.5$, and $h/d = 0.25$.

	HBEM		FEM		δ[%]
	ε_r^{eff}	$Z_c\,[\Omega]$	ε_r^{eff}	$Z_c\,[\Omega]$	
0.1	2.6670	80.106	2.6683	80.370	0.33
0.2	2.5678	55.121	2.5667	55.247	0.23
0.3	2.5038	38.854	2.5042	38.957	0.26
0.4	2.5202	24.502	2.5192	24.629	0.52

B. Example 2

Geometry of the stripline with a rectangular cross-section placed horizontally, off-centered, into the dielectric layer of permittivity ε_2, is shown in Fig. 6. Analysis of this structure is also possible using the HBEM.

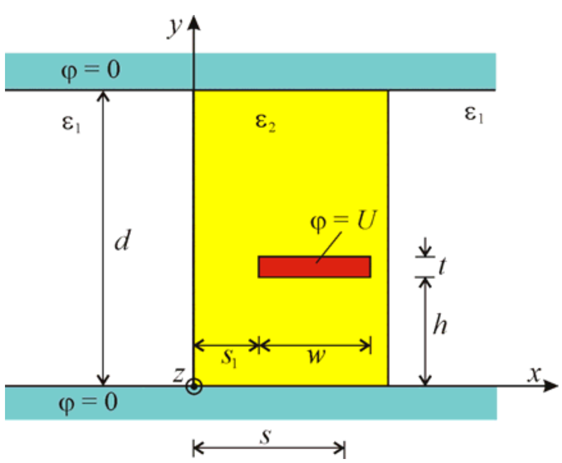

Fig. 6. Stripline with rectangular cross-section.

Applying the procedure described in section II, a computer code for the calculation of the effective dielectric permittivity and the characteristic impedance is developed. Values of the effective dielectric permittivity, characteristic impedance and the computation time for: $\varepsilon_{r1} = 1$, $\varepsilon_{r2} = 3$, $s/d = 0.5$, $s_1/s = 0.2$, $h/d = 0.3$, $w/s = 0.5$, and $t/w = 0.1$, are presented in Table IV. N_{tot} denotes the total number of unknowns. A good convergence of the results is achieved for the short computation time. The convergent rate is linear, as well as in example 1. The calculation was performed on a computer with dual core INTEL processor 2.8 GHz and 4 GB of RAM.

Table IV: Convergence of the results and computation time.

N_{tot}	ε_r^{eff}	$Z_c\,[\Omega]$	t(s)
264	2.4871	75.239	8.5
348	2.4873	75.283	14.7
436	2.4874	75.313	23.1
520	2.4875	75.332	32.7
604	2.4876	75.346	44.4
692	2.4876	75.358	58.6
776	2.4877	75.366	73.2
858	2.4877	75.372	91.8
946	2.4877	75.379	109.5
1030	2.4878	75.384	130.2
1114	2.4878	75.388	152.9
1202	2.4878	75.392	180.0

Equipotential contours and a distribution of polarized charges per unit length along boundary surfaces are shown in Figs. 7 and 8, respectively, for: $\varepsilon_{r1} = 1$, $\varepsilon_{r2} = 3$, $s/d = 0.5$, $s_1/s = 0.2$, $h/d = 0.3$, $w/s = 0.5$, and $t/w = 0.1$.

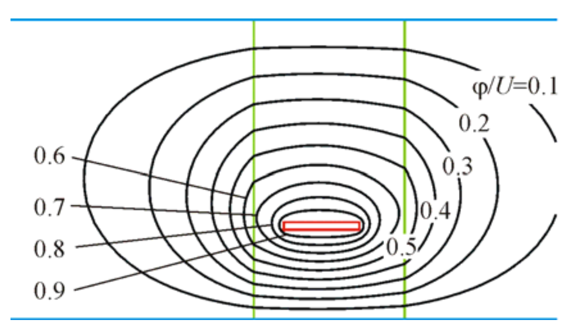

Fig. 7. Equipotential contours.

Using the FEM software, the same stripline model was created, in order to verify the accuracy of the HBEM results. In Tables V and VI, the comparison of the effective dielectric permittivity and characteristic impedance as well as a deviation between the HBEM and FEM results, are presented. The maximal deviation is 0.22 %.

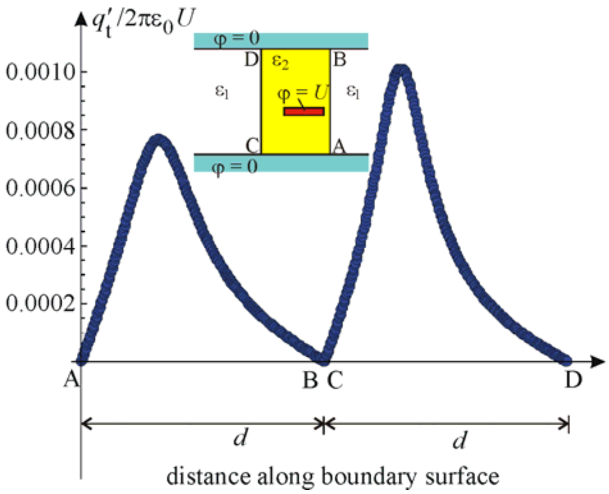

Fig. 8. Distribution of polarized charges per unit length along the boundary surfaces.

Table V: Comparison between the values of dielectric permittivity and characteristic impedance of stripline versus s_1/s and h/d for: $\varepsilon_{r1} = 1$, $\varepsilon_{r2} = 3$, $s/d = 0.5$, $w/s = 0.5$, and $t/w = 0.05$.

$\frac{s_1}{s}$	$\frac{h}{d}$	HBEM		FEM	
		ε_r^{eff}	$Z_c\,[\Omega]$	ε_r^{eff}	$Z_c\,[\Omega]$
0.1	0.1	2.7350	44.646	2.7348	44.634
	0.2	2.5588	65.889	2.5587	65.834
	0.3	2.4540	78.241	2.4539	78.166
	0.4	2.3985	84.833	2.3986	84.750
	0.5	2.3825	86.756	2.3825	86.666
0.2	0.1	2.7986	44.135	2.7985	44.126
	0.2	2.6214	65.097	2.6214	65.045
	0.3	2.5087	77.382	2.5087	77.307
	0.4	2.4485	83.963	2.4485	83.879
	0.5	2.4310	85.886	2.4311	85.795
0.25	0.1	2.8056	44.080	2.8055	44.069
	0.2	2.6289	65.005	2.6289	64.953
	0.3	2.5153	77.281	2.5153	77.206
	0.4	2.4545	83.860	2.4545	83.777
	0.5	2.4369	85.783	2.4370	85.695

Table VI: Comparison between the values of dielectric permittivity and characteristic impedance of stripline versus w/s for: $\varepsilon_{r1} = 1$, $\varepsilon_{r2} = 3$, $s/d = 0.5$, $s_1/s = 0.2$, $h/d = 0.3$, and $t/w = 0.05$.

$\frac{w}{s}$	HBEM		FEM		$\delta[\%]$
	ε_r^{eff}	$Z_c\,[\Omega]$	ε_r^{eff}	$Z_c\,[\Omega]$	
0.1	2.6304	133.670	2.6300	133.371	0.22
0.2	2.5980	109.038	2.5983	108.878	0.15
0.3	2.5746	94.713	2.5746	94.611	0.11
0.4	2.5467	84.782	2.5468	84.697	0.10
0.5	2.5087	77.382	2.5087	77.307	0.03
0.6	2.4556	71.694	2.4556	71.628	0.09
0.7	2.3817	67.310	2.3817	67.251	0.09

IV. CONCLUSION

The HBEM is applied to the 2D striplines analysis. Two quasi-static parameters are calculated: the effective dielectric permittivity and the characteristic impedance. The FEM software was applied as validation of HBEM results accuracy. The maximal results deviation is less than 0.55 %. In both examples, the corresponding FEM models of striplines were created with a few hundred of thousands of finite elements. Such large number of finite elements is necessary from the point of this software accuracy. The comparison with HBEM is given only in order to verify the accuracy of the HBEM results.

The application of HBEM is very efficient and simple in the 2D striplines analysis. Fast convergence of the results and short computation time are some of this method advantages. The method can be also successfully applied to the arbitrary number of conductors and arbitrary number of dielectric layers. A large variety of very complex 2D and 3D problems, regarding striplines with or without symmetry, can be also solved. That will be the subject of our future research.

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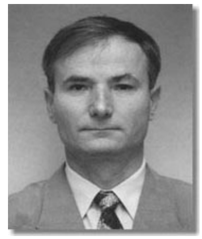

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