VERY SIMPLE AND ACCURATE COMPUTER-AIDED-DESIGN (CAD) MODELS DEVELOPED BY GENETIC PROGRAMMING FOR THE QUASI-STATIC ANALYSIS OF UNSHIELDED SUSPENDED AND INVERTED MICROSTRIP LINES

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Abstract: *Very simple computer-aided-design models are introduced to determine the characteristic parameters such as effective permittivities and characteristic impedances of unshielded suspended and inverted microstrip lines. Computer-aided-design models are determined with the use of the genetic programming. The results of computer-aided-design models are compared with the results of quasi-static analysis, experimental works available in the literature and a commercial electromagnetic simulator. The comparison results clearly show that computer-aided-design* models *proposed in this work are in very good agreement with the simulation, theoretical and experimental results for the suspended and inverted microstrip lines. The design parameter ranges in this work are* $2 \leq \varepsilon_{r2} \leq 20$, $0.5 \leq w/b \leq 10$, $0.1 \leq a/b \leq 1.5$, *and the respective characteristic impedances of unshielded suspended and inverted microstrip lines are* $28\Omega \leq Z_0 \leq 185\Omega$, *and* $24\ \Omega \leq Z_0 \leq 159\ \Omega$, *respectively. It is observed that the accuracies of computer-aided-design models proposed in this paper are good enough for the most practical cases.*

Keywords: *Suspended and inverted microstrip, Computer-aided-design models, Genetic programming, Characteristic impedance, Effective permittivity*

1. Introduction

Suspended and inverted microstrip (S&IM) lines are very useful transmission lines and they have an air gap between dielectric substrate and ground plane. They have many advantages such as lower dispersion, lower propagation loss and easy connections to conventional microstrip lines. S&IM lines are used to manufacture most of the microstrip components, such as amplifiers, mixers, power dividers, frequency multipliers, and directional couplers. Due to the symmetrical shielding and the wide range of characteristic impedance values achievable make these transmission lines particular suitable for filters [1, 2].

Many researches dealing with S&IM lines have been realized in the literature and they can be classified in three groups [3]. The first group consists of analytical works related with rigorous electromagnetic analysis of S&IM lines and their discontinuities. The works about the applications of S&IM lines such as filters, couplers, phase shifters, power combiners, mixers and antennas can be added in the second group. The third group contains many research papers about computer-aided-design (CAD) models for analyzing of different S&IM lines.

Four CAD models have been proposed for the quasi-static analysis of unshielded S&IM lines in the literature [4-9]. The first CAD model was reported in 1985 [4] and the accuracy of this model is better than ±1 % according to the exact theoretical data reproduced by Tomar et.al [3]. This model contains an empirical expression depended on the geometrical dimensions of unshielded S&IM lines for the effective permittivity and it is valid for $\varepsilon_{r2} \leq 6$. The most important disadvantage of this work is the restriction of the dielectric constant $\varepsilon_{r2} \leq 6$ for substrate material, because substrate materials with $\varepsilon_{r2} \geq 6$ are often used in practice for example alumina (ε_{r2} = 9.6) and GaAs (ε_{r2} = 12.9). The second quasi-static CAD model is a generalized of the first CAD model [5]. This model is valid for a wider range of design parameters and the accuracy of this model according to the exact theoretical data reproduced in [3] is better than ±0.6 % for both unshielded suspended and inverted

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microstrip lines. This model contains a polynomial expression depending on geometrical dimensions of the lines for the effective permittivity. The third CAD model was first reported by Svacania in 1992 [6, 7] and later Schellenberg has modified the Svacania's formulas, uses a conformal mapping approach, coupled with curve-fitting to obtained theoretical data, and proposed two closed-form equations for the effective permittivities of unshielded S&IM lines [8]. These models are valid for $\varepsilon_{r2} \leq 12.9$. The claimed accuracies of these models are better than ±0.65 % and ±1 % for unshielded S&IM lines, respectively [8]. The last CAD model was proposed by Yıldız and Saracoğlu for the effective permittivities of unshielded S&IM lines [9]. This model is based on artificial neural network and does not contain closed-form equations.

The analysis CAD models proposed in the literature except last model contain long mathematical expressions and require extensive calculations to compute the effective permittivities of unshielded S&IM lines. Beside, these models do not have good accuracy except the second model [5]. More significantly, these CAD models do not contain closed-form equations to directly compute the characteristic impedances of unshielded S&IM lines and they are valid for only the effective permittivities of these lines. In the literature, the characteristic impedances of unshielded S&IM lines are calculated by using a formula depending on the effective permittivities of unshielded S&IM lines and characteristic impedance of a conventional microstrip line. For this reason, this formula becomes very complex, contains very long mathematical expressions and requires extensive calculations to compute the characteristic impedances of unshielded S&IM lines. Consequently, CAD models proposed in the literature are not very suitable to compute the propagation characteristics of S&IM lines. The aim of this paper is to present accurate and very simple CAD models developed by genetic programming (GP) for both effective permittivities and characteristic impedances of unshielded S&IM lines.

GP is an automated method for creating a working computer program from a high-level problem statement of the problem and it was applied to many engineering problems [10-15]. According to our researches, GP was also successfully applied to the design problems of microwave planar transmission lines for the first time by Kişioğlu and Yıldız [16]. In this application, new and accurate synthesis models developed by GP were proposed to calculate the geometrical dimensions of coplanar waveguide with a finite width ground plane. New synthesis models consist of two closed-form design equations. One of them calculates the strip width of the coplanar waveguide and the other calculates the sloth width of the coplanar waveguide having a desired characteristic impedance for a given dielectric substrate material. In order to show the validities of proposed synthesis models for the coplanar waveguide with a finite width ground plane, obtained results are compared with the results of quasi-static analysis and very good agreements between them were observed [16].

In this paper, CAD models were developed by using GP to directly calculate both the effective permittivities and characteristic impedances of unshielded S&IM lines. CAD models can be used to easily and accurately calculate the propagation characteristics of unshielded S&IM lines. The ranges of validties of these CAD models valid very wide region and they are $2 \leq \varepsilon_{r2} \leq 20$, $0.5 \leq w/b \leq 10$, $0.1 \leq a/b \leq 1.5$. In order to show the accuracies and validities of CAD models produced by GP, their results are compared with the results of theoretical [2, 5, 8], experimental works [17-19] available in the literature, and a commercial electromagnetic simulator HFSS [3].

2. Genetic Programming

Soft computing can be defined to be a collection of some computational techniques that try to imitate human intelligence for creating solution of complex problems, which attempt to overcome the impreciseness, uncertainty in the problem by some human-like capabilities such as reasoning, learning, decision making,. Components of soft computing include neural networks, fuzzy systems, evolutionary algorithms such as genetic algorithms, GP and swarm intelligence based algorithms.

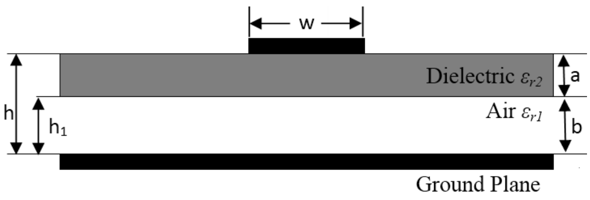
GP was developed by Koza and adopted from the process of natural evolution and genetics [20]. GP belongs to the class of evolutionary algorithms which is based on the "principle of survival of the fittest". GP is however a relatively new addition to the group of other evolutionary algorithm techniques such as genetic algorithms, evolutionary programming and evolution strategies [21]. GP is similar to genetic algorithm [22]. The main difference between GP and genetic algorithm is that GP represents a solution as a tree instead of a binary string used in genetic algorithm.

GP differs from other data-driven models such as fuzzy rule-based systems and artificial neural networks [23]. It has found application mostly in the area of symbolic regression. The aim is to find a functional relationship between input and output variables in the symbolic regression problems. GP is a computer program which is often given as a tree model. There are terminals in the tree model where the internal nodes correspond to a set of functions used in the program and the external nodes indicate variables and constants used as the input to functions [24]. GP has been used as an optimization technique on the variety of problems and applications [25, 26].

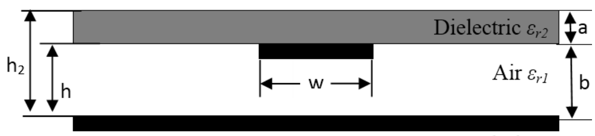
In applying genetic programming to a problem, there are five major preparatory steps. These five steps involve determining terminal set, function set, fitness function, control parameter, and termination criteria. The first step is the set of terminals which may consist of the program's external inputs, functions with no arguments and constants. The second step is the set of primitive functions that are to be used to generate the mathematical expression that attempts to fit the given finite sample of data. The third step is the design of a fitness measure function. The fourth step includes determining the values of control parameters and in the last step a termination criterion for the algorithm is defined [27, 28].

3. CAD Models Developed by Genetic Programming for Unshielded S&IM Lines

The configurations of unshielded S&IM lines are shown in Figure 1. It is assumed that all conductors used in transmission lines are infinitely thin and perfectly conducting. GP finds a functional relationship between input and output variables for analyzing unshielded S&IM lines. In the analysis models, the inputs are relative permittivity (ε_{r2}), geometrical dimensions of the transmission lines (*a/b*, *w/b*) and output is effective permittivity (ε_{eff}) or characteristic impedance (Z_0) of unshielded S&IM lines.



a) Unshielded SM line



b) Unshielded IM line

Figure 1. Configurations of unshielded S&IM lines

CAD models to be produced by GP for the quasi-static analysis of unshielded S&IM lines are essentially derived from the data set. The data set used in this paper has been obtained from the quasi-static analysis results [5]. The data set includes 3600 samples for each unshielded S&IM lines, separately. The ranges of the parameters in the data set are $2 \le \varepsilon_{r2} \le 20$, $0.5 \le w/b \le 10$, $0.1 \le a/b \le 1.5$, and the respective characteristic impedances of unshielded S&IM lines are $28\Omega \le Z_0 \le 185\Omega$, and $24\ \Omega \le Z_0 \le 159\ \Omega$, respectively.

In order to find the suitable CAD models produced by GP for the quasi-static analysis of unshielded S&IM lines, many experiments were carried out. In these experiments, the most suitable values of population size, mutation rate, reproduction rate and crossover rate are chosen as 50, 0.1, 0.05 and 0.85, respectively. After many trials, accurate and very simple analysis CAD models were determined to compute the characteristic parameters of unshielded S&IM lines for a given relative dielectric constant ε_{r2} and physical dimensions (*w/b* and *a/b*) of substrate material. The analysis CAD models determined by GP for calculating the characteristic impedance and effective permittivity of unshielded SM line, which produce very good results, are given below;

$$Z_0 = \eta_0 \cdot \left[\alpha_1 + \alpha_2 \cdot u + \alpha_3 \cdot \varepsilon_{r2} \cdot x - \frac{\alpha_4}{\alpha_5 \cdot u + \cos(\alpha_6 + x)} - \frac{\alpha_7 + \alpha_8 \cdot u \cdot \sin(\alpha_9 \cdot x)}{\alpha_{10} + \varepsilon_{r2}} - \alpha_{11} \cdot x \cdot u \right]^{-1} \tag{1}$$

$$\varepsilon_{eff} = \alpha_1 + \alpha_2 \cdot x - \frac{\alpha_3 \cdot x}{\alpha_4 + \varepsilon_{r2}} + \frac{\alpha_5 \cdot \varepsilon_{r2} \cdot x - \alpha_6 \cdot x^2}{u + \alpha_7 \cdot \varepsilon_{r2} + \alpha_8 \cdot x^{\alpha_9}} \tag{2}$$

The analysis CAD models produced by GP for computing the characteristic impedance and effective permittivity of unshielded IM line are given below;

$$Z_0 = \eta_0 \cdot \left[\alpha_1 + \alpha_2 \cdot u + \alpha_3 \cdot \sqrt{\varepsilon_{r2} \cdot x} - \frac{\alpha_4 + \alpha_5 \cdot x \cdot \sqrt{\varepsilon_{r2} \cdot x}}{\alpha_6 + \alpha_7 \cdot u + \alpha_8 \cdot u^2} - \alpha_9 \cdot x \right]^{-1} \tag{3}$$

$$\varepsilon_{eff} = \alpha_1 + \frac{\alpha_2 \cdot \varepsilon_{r2} + \alpha_3 \cdot \varepsilon_{r2} \cdot x - \alpha_4 \cdot x \cdot \varepsilon_{r2}^{\ 2} - \alpha_5 \cdot \varepsilon_{r2} \cdot x^2}{\alpha_6 + u + x} - \alpha_7 \cdot x^2 - \alpha_8 \cdot \varepsilon_{r2} \cdot x^2 \tag{4}$$

with

$$u = \frac{w}{b} \quad \text{and} \quad x = \frac{a}{b} \tag{5}$$

where $\eta_0 = 120\pi\ \Omega$ is the intrinsic impedance of free space and (α_1, α_2,…., α_{11}) are unknown coefficients.

The values of unknown coefficients in the analysis CAD models are optimally found by GP and the results are listed in Table 1. The analysis CAD models are obtained by substituting the values of the coefficients in Equations 1, 2, 3 and 4 for the calculation of characteristic parameters of unshielded S&IM lines.

Table 1. The values of the coefficients used in CAD models for the unshielded S&IM lines

		α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α_9	α_{10}	α_{11}
Suspended microstrip	(Z_0)	3.6450	0.9952	0.0533	1.2319	0.9952	5.7193	5.6497	0.9952	1.2505	3.3701	0.2066
	(ε_{eff})	1.0501	0.7993	1.7814	1.0508	0.4085	0.5734	0.0331	1.5063	1.0508		
Inverted microstrip	(Z_0)	2.0540	1.0569	0.7599	3.4134	0.7029	3.7305	3.7305	1.4177	0.3105		
	(ε_{eff})	1.0068	0.0249	0.4235	0.0063	0.0249	0.5449	0.0152	0.0030			

4. Numerical Results and Discussion

In this paper, analysis CAD models developed by GP for unshielded S&IM lines are presented. Many extensive comparisons have been made to confirm the accuracies and validities of CAD models proposed in this work for both unshielded S&IM lines. The results of CAD models are compared with the results of quasi-static analysis, experimental works available in the literature and a commercial electromagnetic simulator HFSS.

The first comparison is made for the effective permittivities and characteristic impedances of unshielded S&IM lines according to the ratio of normalized strip width (*w/b*) for different *a/b* ratios (ε_{r2} = 3.78). The obtained results are given in Figures 2 and 3. In these figures, the results of CAD models are compared with the results of Tomar and Bhartia's work [5] known as the best accurate model in the literature. As it can be clearly seen from these figures, there are very good agreement between our CAD model results and Tomar and Bhartia's results.

The results of second comparison are shown in Tables 2 and 3 for characteristic impedances and effective permittivities of unshielded S&IM lines with different geometrical dimensions and relative permittivities, respectively. In these tables, calculated results obtained from CAD models generated by GP are compared with the results of variational method in Fourier transform domain [2] and CAD models [5, 8] available in the literature, and a commercial electromagnetic simulator HFSS [3].

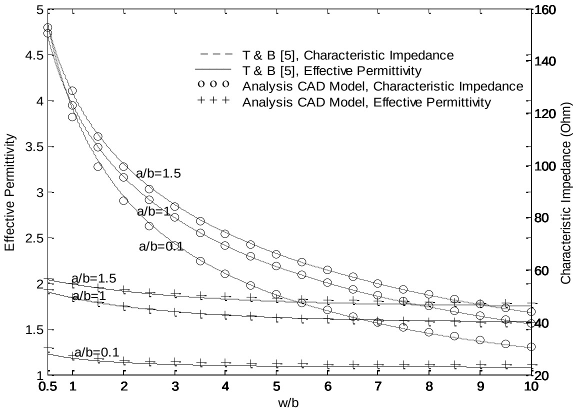


Figure 2. Comparisons between CAD models produced by GP and T&B's model [5] for the effective permittivity and characteristic impedance of unshielded SM line (ε_{r2}=3.78)

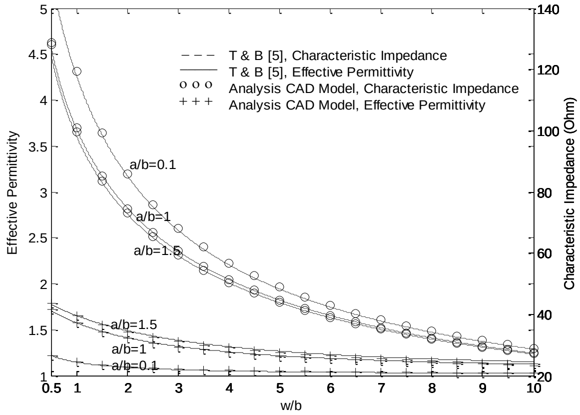


Figure 3. Comparisons between CAD models produced by GP and T&B's model [5] for the effective permittivity and characteristic impedance of unshielded IM line (ε_{r2}=3.78)

Table 2. Results of CAD model developed by GP, analysis models available in the literature and HFSS for the characteristic impedance and effective permittivity of unshielded SM line

ε_{r2}	a/b	w/b	Analysis Model [2]		Analysis Model [5]		Analysis Model [8]		HFSS (1 GHz) [3]		CAD model (This work)	
			$\sqrt{\varepsilon_{eff}}$	Z_0 (Ω)	$\sqrt{\varepsilon_{eff}}$	Z_0 (Ω)	$\sqrt{\varepsilon_{eff}}$	Z_0 (Ω)	$\sqrt{\varepsilon_{eff}}$	Z_0 (Ω)	$\sqrt{\varepsilon_{eff}}$	Z_0 (Ω)
2.22	0.2	0.5	1.1018	161.84	1.0955	162.14	1.1146	159.35	1.1027	162.95	1.1345	167.35
		1	1.0830	127.11	1.0816	126.61	1.0987	124.64	1.0826	129.38	1.1038	128.69
		2	1.0681	92.83	1.0664	92.35	1.0825	90.98	1.0668	96.16	1.0809	92.93
		3	1.0613	74.22	1.0587	73.85	1.0740	72.80	1.0611	75.43	1.0716	74.31
		4	1.0574	62.18	1.0547	61.86	1.0688	61.04	1.0574	62.80	1.0665	62.35
		5	1.0548	53.65	1.0526	53.36	1.0653	52.72	1.0550	53.37	1.0633	53.87
		6	1.0530	47.65	1.0516	46.98	1.0628	46.48	1.0540	48.50	1.0611	47.49
		7	1.0517	42.26	1.0512	42.00	1.0608	41.62	1.0531	42.51	1.0595	42.50
		8	1.0508	38.24	1.0508	38.01	1.0593	37.70	1.0515	38.71	1.0583	38.48
		9	1.0500	34.94	1.0502	34.75	1.0581	34.48	1.0512	34.33	1.0573	35.16
		10	1.0494	32.17	1.0489	32.04	1.0572	31.79	1.0502	31.46	1.0566	32.38
12.9	1	0.5	1.9184	108.80	1.9121	108.81	1.9202	108.4	1.9162	109.66	1.9109	108.54
		1	1.8220	92.07	1.8296	91.18	1.8257	91.37	1.8237	92.14	1.8228	92.67
		2	1.7096	74.58	1.7149	73.77	1.7072	74.10	1.7026	75.05	1.7075	75.08
		3	1.6417	63.98	1.6401	63.46	1.6373	63.57	1.6377	64.60	1.6351	64.33
		4	1.5957	56.40	1.5883	56.09	1.5912	55.99	1.5903	56.59	1.5853	56.64
		5	1.5622	50.60	1.5510	50.41	1.5583	50.17	1.5560	50.57	1.5489	50.75
		6	1.5367	45.97	1.5232	45.84	1.5336	45.53	1.5310	46.57	1.5211	46.03
		7	1.5164	42.17	1.5019	42.07	1.5142	41.73	1.5076	42.12	1.4991	42.16
		8	1.4999	38.99	1.4849	38.90	1.4986	38.54	1.4926	38.15	1.4814	38.90
		9	1.4862	36.27	1.4707	36.20	1.4856	35.84	1.4826	35.43	1.4667	36.13
		10	1.4746	33.93	1.4582	33.88	1.4747	33.50	1.4741	33.52	1.4544	33.73

Finally, to consolidate the validities of CAD models proposed in this paper, their effective permittivity results are also compared with the results of experimental works [17-19] for both unshielded S&IM lines with different geometrical dimensions and relative permittivities. The calculated results of CAD models generated by GP in this work are given in Table 4. The results of variational method [2] and analysis CAD models [5, 8] available in the literature and HFSS results are also added in Table 4. The calculated values for effective permittivity obviously show that there are very good agreement again among CAD models developed by GP, theoretical [2, 5, 8], experimental results [17-19] available in the literature and HFSS [3].

Table 3. Results of CAD model developed by GP, analysis models available in the literature and HFSS for the characteristic impedance and effective permittivity of unshielded IM line

ε_{r2}	a/b	w/b	Analysis Model [2]		Analysis Model [5]		Analysis Model [8]		HFSS (1 GHz) [3]		CAD model (This work)	
			$\sqrt{\varepsilon_{eff}}$	Z_0 (Ω)	$\sqrt{\varepsilon_{eff}}$	Z_0 (Ω)	$\sqrt{\varepsilon_{eff}}$	Z_0 (Ω)	$\sqrt{\varepsilon_{eff}}$	Z_0 (Ω)	$\sqrt{\varepsilon_{eff}}$	Z_0 (Ω)
2.22	1	0.5	1.1608	144.59	1.1636	143.36	1.1618	143.59	1.1601	148.64	1.1956	142.02
		1	1.1348	112.44	1.1359	111.37	1.1711	108.03	1.1345	113.41	1.1586	109.90
		2	1.1015	81.80	1.1006	80.95	1.0885	81.85	1.1036	80.72	1.1142	79.79
		3	1.0810	65.43	1.0792	64.70	1.0701	65.25	1.0826	65.73	1.0886	64.06
		4	1.0673	54.87	1.0651	54.23	1.0583	54.58	1.0686	56.34	1.0719	53.89
		5	1.0575	47.39	1.0552	46.82	1.0501	47.05	1.0578	47.79	1.0601	46.64
		6	1.0502	41.77	1.0479	41.26	1.0440	41.41	1.0502	41.43	1.0514	41.16
		7	1.0444	37.39	1.0425	36.91	1.0393	37.03	1.0474	37.27	1.0447	36.85
		8	1.0398	33.86	1.0383	33.42	1.0355	33.51	1.0416	33.86	1.0393	33.38
		9	1.0360	30.96	1.0350	30.54	1.0325	30.62	1.0392	30.83	1.0350	30.50
		10	1.0328	28.52	1.0325	28.13	1.0299	28.20	1.0300	29.48	1.0313	28.09
9.8	0.6	0.5	1.5434	108.75	1.5485	107.73	1.4966	111.47	1.5440	110.28	1.5423	107.92
		1	1.4349	88.92	1.4430	87.67	1.5396	82.17	1.4279	89.76	1.4336	88.34
		2	1.3174	68.39	1.3177	67.61	1.3286	67.06	1.3161	69.44	1.3102	67.79
		3	1.2521	56.49	1.2462	56.03	1.2613	55.36	1.2329	57.15	1.2416	56.09
		4	1.2097	48.41	1.2004	48.12	1.2177	47.44	1.1996	48.01	1.1977	48.14
		5	1.1795	42.48	1.1689	42.27	1.1869	41.62	1.1790	42.21	1.1627	42.27
		6	1.1568	37.92	1.1459	37.73	1.1640	37.14	1.1615	37.04	1.1447	37.72
		7	1.1390	34.28	1.1287	34.10	1.1463	33.57	1.1446	32.69	1.1274	34.07
		8	1.1246	31.31	1.1154	31.11	1.1321	30.65	1.1269	29.99	1.1137	31.08
		9	1.1128	28.82	1.1048	28.61	1.1205	28.21	1.1050	27.62	1.1026	28.57
		10	1.1028	26.71	1.0964	26.49	1.1108	26.15	1.1050	25.76	1.0934	26.45

Table 4. Results of CAD models developed by GP, experimental works, analysis models published in the literature and HFSS for the effective permittivities of unshielded S&IM lines

	ε_{r2}	a/b	w/b	Effective Permittivity (ε_{eff})							
				Experimental Data			Analysis Model [2]	Analysis Model [5]	Analysis Model [8]	HFSS (1 GHz) [3]	CAD model (This work)
				[18]	[17]	[19]					
Suspended Microstrip	2.55	1.6069	0.6541	1.7566	--	--	1.5976	1.6002	1.5847	1.6703	1.5996
		0.8034	0.4727	1.5986			1.4879	1.4879	1.4751	1.5587	1.5609
		0.4017	0.3041	1.4775			1.3959	1.3806	1.3853	1.4568	1.5098
		0.2008	0.1775	1.3841			1.3273	1.2760	1.3149	1.3884	1.4554
Inverted Microstrip	3.78	1.333	1	--	1.5269	--	1.6276	1.6340	1.6215	1.6240	1.6340
			2		1.3763		1.4701	1.4689	1.4577	1.4660	1.4600
			3		1.2735		1.3740	1.3675	1.3684	1.3590	1.3574
			4		1.2137		1.3098	1.3000	1.3092	1.2929	1.2898
			5		1.1709		1.2642	1.2524	1.2670	1.2450	1.2418
		0.333	0.5	--	--	1.3689	1.4551	1.4682	1.3964	1.4299	1.4297
			1.0			1.2544	1.3375	1.3391	1.3581	1.3165	1.3163
			2.0			1.1664	1.2285	1.2181	1.2301	1.2078	1.2077
			3.0			1.1342	1.1737	1.1608	1.1744	1.1552	1.1552
			4.0			1.1025	1.1340	1.1278	1.1408	1.1242	1.1241
			5.0			1.0712	1.1168	1.1063	1.1185	1.1038	1.1037

Similar good results are also observed for all unshielded S&IM lines to be analyzed. The average percentage errors of CAD models for the characteristic impedance and effective permittivity are calculated to be 0.79% and 0.74%, respectively, for 3600 unshielded SM line samples. The average percentage errors of the CAD models for the characteristic impedance and effective permittivity are calculated to be 0.33% and 0.68%, respectively, for 3600 unshielded IM line samples, as compared with the results of quasi-static analysis [5].

Consequently, the agreement among the results of CAD models developed by GP, analysis CAD models, the results of variational method in Fourier transform domain, experimental works available in the literature, and HFSS obviously confirm the validity of CAD models proposed in this work for analyzing unshielded S&IM lines. The results also illustrate the performance of GP in obtaining high quality solutions.

5. Conclusions

In this work, accurate and very simple analysis CAD models for unshielded S&IM lines were developed by using GP. The proposed CAD models allow the designers to directly and easily calculate the characteristic parameters such as characteristic impedances and effective permittivities of unshielded S&IM lines. The results of CAD models proposed in this work are in good agreement with the result of theoretical, experimental works available in the literature and HFSS. It was observed that the accuracies of CAD models for unshielded S&IM lines were good enough for the most practical cases. The proposed CAD models are also very simple and useful for many microwave engineering applications. Finally, the procedure used in this paper could be also useful for developing simple and accurate analysis and design equations for other microwave transmission lines having different geometrical structure.

6. References

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