CAD Models for Suspended and Inverted Microstrip

J. M. Schellenberg, *Senior Member, IEEE*

***Abstract*—The accuracies of CAD models for suspended and inverted microstrip are examined, and new models are proposed. The models are compared over the range of 0.1 $\leq w/h \leq$ 10 and for ϵ_r values of 3.78 and 12.9. Of the three models examined, the Tomar and Bhartia (T&B) model is shown to be the most accurate. For ϵ_r = 12.9 (the worst case), the T&B model shows maximum and average errors of 2.94 and 1.28% respectively over its valid range. New CAD models are presented which demonstrate significantly improved accuracy and range of convergence. For suspended and inverted microstrip, the new models demonstrate worst case errors of 0.65 and 1.02%, respectively, and average errors of 0.23 and 0.27%, respectively. Further, the new models are valid for the full 0.1 $\leq w/h \leq$ 10 range, and unlike the other models, converge for the limiting cases of either complete substrate filling or a zero thickness substrate.**

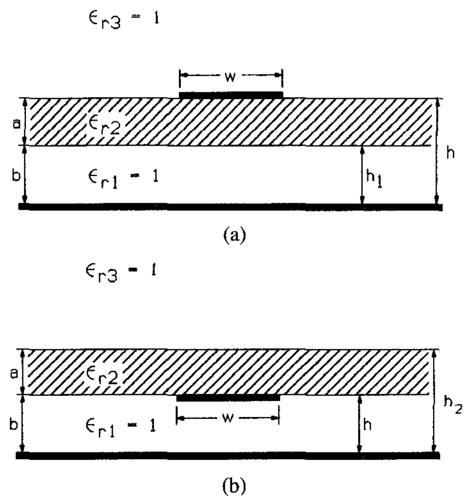

Fig. 1. Geometry of (a) suspended microstrip and (b) inverted microstrip

I. Introduction

SUSPENDED microstrip (SM) and inverted microstrip (IM) are important transmission media for microwave and millimeter wave applications. While these configurations also provide less dispersion than conventional microstrip, the principle reason for their utilization is that these configurations offer lower loss than conventional microstrip [1], [2]. For the same characteristic impedance, substrate thickness and a comparable air gap, the attenuation due to conductor loss (usually the dominate loss) is improved by a factor of typically 2–3. Using these configurations with GaAs MMIC's, for example, it is possible to combine the active devices and lithography advantages of MMIC's with the low loss usually associated with hybrid circuits, thereby yielding a new generation of high-Q MMIC's.

Over the past two decades, considerable effort has been expended to analyze these and similar multilayer microstrip geometries [3]–[10]. While many of these efforts were devoted to complex numerical solutions with little practical utility for design work, recently, several potentially useful CAD models [11]–[14] have emerged. These models are for a zero thickness strip and are quasi-static in nature with no treatment of dispersion. As pointed out in [12], this is generally acceptable since, for practical suspended and inverted microstrip geometries, dispersion is low. This argument is supported by recent numerical results on the dispersion of suspended microstrip [15].

The numerical solution, which served as the basis of comparison for this work, is contained in a commercially available program, MicroZAP™ [16]. MicroZAP™ treats three-layer microstrip like structures, and uses the proven spectral domain approach (SDA) [17] with the strip charge distribution expanded in terms of Chebyshev polynomials modified by the Maxwellian edge singularity. This solution has been compared to exact conformal mapping solutions for single dielectric microstrip and stripline with better than 13-digit agreement. Further, this solution has been compared with Kobayashi's [18], [19] and Shih's [20] two dielectric results, and, in most cases, it shows 5-digit agreement.

This paper focuses on the effective dielectric constant, ϵ_{eff}, of suspended and inverted microstrip. Hammerstad and Jensen [21] have developed an elegantly simply, yet accurate, formula for the characteristic impedance of air filled microstrip. Accurate to better than 0.03% for $w/h <$ 1000, this expression can be used in conjunction with this work to calculate the characteristic impedance, Z_o, of SM and IM as

$$Z_o = Z/(\epsilon_{\text{eff}})^{1/2} \tag{1}$$

where Z is the characteristic impedance of an identical air-filled microstrip line given by the Hammerstad and Jensen expression.

The ϵ_{eff} models presented below are all quasi-static in nature and assume an "open" structure with a zero thickness strip. The geometric parameters are defined in Fig. 1. We will first examine current models, and then will propose some new CAD models.

II. Accuracy of Current Models

The first model, proposed by Pramanick and Bhartia [11] (P&B), consists of a relatively simple empirical expression

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The author is with Schellenberg Associates, Huntington Beach, CA 92647 USA.
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TABLE I
PERCENTAGE ERROR FOR SUSPENDED MICROSTRIP

Er	h1/h	Method \ w/h	0.1	0.2	0.4	0.8	1.0	2.0	4.0	8.0	10
3.78	0.2	P & B	43.02	38.11	33.81	30.06	28.91	24.88	19.46	13.12	11.06
		T & B	-1.58	-0.58	0.62	1.13	0.84	-0.13	366.71	-59.65	-57.79
		Svac.	-4.82	-4.52	-2.97	2.78	7.10	-4.20	-0.82	1.53	2.07
	0.5	P & B	7.33	4.14	2.23	1.56	1.49	0.97	-0.96	-4.36	-5.66
		T & B	-1.73	-0.59	0.21	0.40	0.28	-0.51	-0.74	-8.70	-17.92
		Svac.	-11.31	-11.11	-9.93	-6.56	-4.59	-8.13	-2.89	1.10	2.08
	0.8	P & B	-5.11	-4.52	-2.92	-1.06	-0.59	0.11	-0.50	-2.37	-3.19
		T & B	-6.54	-3.67	-1.24	-0.17	-0.19	-0.93	-1.34	-0.98	-2.50
		Svac.	-13.89	-12.66	-10.45	-7.23	-5.89	-5.84	-1.06	2.59	3.49
12.9	0.2	P & B	63.00	52.95	46.15	42.75	42.32	41.85	39.61	33.82	31.37
		T & B	-10.15	-8.63	-7.33	-6.42	-6.27	-7.91	-25.77	-61.72	-67.36
		Svac.	-23.76	-23.13	-19.54	-5.50	6.30	-20.63	-11.18	-3.31	-1.32
	0.5	P & B	-12.28	-15.67	-16.66	-15.07	-14.08	-10.38	-7.72	-7.70	-8.32
		T & B	-4.12	-1.15	0.86	1.28	1.04	-0.55	-1.96	-8.01	-16.52
		Svac.	-39.10	-38.40	-36.09	-30.32	-27.05	-28.81	-17.67	-7.59	-4.87
	0.8	P & B	-27.73	-26.06	-22.71	-18.11	-16.53	-11.80	-8.32	-7.13	-7.28
		T & B	-8.41	-3.76	-0.45	0.30	-0.04	-1.83	-2.94	-2.34	-2.49
		Svac.	-41.24	-38.97	-35.15	-29.27	-26.77	-22.85	-12.82	-4.14	-1.84

TABLE II
EFFECTIVE DIELECTRIC CONSTANT FOR SUSPENDED MICROSTRIP

Er	h1/h \ w/h	0.1	0.2	0.4	0.8	1.0	2.0	4.0	8.0	10
3.78	0.0	2.5688	2.6051	2.6587	2.7417	2.7773	2.9207	3.1026	3.2895	3.3453
	0.2	2.2998	2.2841	2.2629	2.2365	2.2280	2.2118	2.2251	2.2631	2.2776
	0.5	1.9948	1.9361	1.8608	1.7701	1.7398	1.6560	1.6010	1.5743	1.5701
	0.8	1.6367	1.5511	1.4561	1.3653	1.3394	1.2727	1.2264	1.1982	1.1922
12.9	0.0	7.6588	7.8069	8.0282	8.3760	8.5270	9.1421	9.9330	10.7515	10.9959
	0.2	5.5170	5.3137	5.0507	4.7172	4.5975	4.2301	3.9556	3.8107	3.7861
	0.5	4.0638	3.7739	3.4299	3.0397	2.9107	2.5367	2.2489	2.0609	2.0190
	0.8	2.7728	2.5026	2.2174	1.9440	1.8634	1.6436	1.4773	1.3656	1.3398

for the effective dielectric constant in terms of $\ln(a/b)$. This model is reported to be accurate to within $\pm 1\%$ for $1 \le w/b \le 8$, $0.2 \le a/b \le 1$ and $\epsilon_r \le 6$.

The second model, proposed by Tomar and Bhartia [12] (T&B), consists of a polynomial expansion for the effective dielectric constant in w/b and a/b with the coefficients of the polynomials determined by least-square curve fitting to theoretical data. This model is reported to be accurate to better than 0.6% over the range $0.5 \le w/b \le 10$ and $0.05 \le a/b \le 1.5$ and ϵ_r up to 20.

The third model, proposed by Svacina [13], [14], is based on Wheeler's classical conformal mapping solution [22], [23] for microstrip. No conclusive accuracy results are reported in this work. However, it is stated that for ϵ_r values less than 30, "the accuracy is quite satisfactory and comparable with the accuracy of other, more complicated and more time consuming calculating methods."

A. Suspended Microstrip

The effective dielectric constant for SM as computed using these three methods is compared to the exact theoretical value in Table I. The models are compared over the parameter ranges $0.1 \le w/h \le 10$, $0.2 \le h_1/h \le 0.8$ and $\epsilon_r = 3.78$ (fused silica) and 12.9 (GaAs). The exact theoretical values for SM are summarized in Table II.

First of all, the P&B model has a very limited range of utility. With $\epsilon_r = 3.78$, over its claimed range of accuracy (0.5 $\le w/h \le 4$ for $h_1/h = .5$ and $0.2 \le w/h \le 1.6$ for $h_1/h = 0.8$), the P&B model exhibits an average error of 1.64% and a maximum error of 4.52%. This model is not valid for $\epsilon_r > 6$, and hence exhibits large errors for $\epsilon_r = 12.9$.

The T&B model, which is an expanded version of the P&B model, is valid over a much wider range of parameters. For $\epsilon_r = 3.78$, the T&B model shows an average error of 0.46% for $h_1/h = 0.5$ and $0.2 \le w/h \le 5$ and 2.12% for $h_1/h = 0.8$ and $0.1 \le w/h \le 2$. For $\epsilon_r = 12.9$, the T&B model shows an average error of 1.1% and 2.5% for its valid w/h range with $h_1/h = 0.5$ and 0.8, respectively. Over its claimed ranged of validity, the T&B model seems to have the poorest accuracy for small values of w/h. For example, with $\epsilon_r = 12.9$ and $h_1/h = 0.8$, the maximum error of 8.41% occurs for $w/h = 0.1$. In general, for $h_1/h = 0.8$ (thin substrate) the T&B model demonstrates reasonable accuracy (better than 3%) for values

TABLE III
PERCENTAGE ERROR FOR INVERTED MICROSTRIP

Er	h2/h	Method \ w/h	0.1	0.2	0.4	0.8	1.0	2.0	4.0	8.0	10
3.78	1.2	P & B	-6.56	-5.70	-3.87	-1.70	-1.08	0.18	0.05	-1.78	-2.70
		T & B	-0.96	0.53	0.98	0.29	-0.07	-1.05	-1.26	-0.86	-0.65
		Svac.	-6.06	- 5.28	- 3.87	- 2.39	- 2.11	- 4.81	- 3.45	- 2.24	- 1.91
	2.0	P & B	12.56	7.10	2.92	0.53	0.21	0.36	0.52	-1.87	-3.35
		T & B	-1.64	-0.25	0.64	0.79	0.71	0.22	-0.42	-0.70	-0.53
		Svac.	1.76	1.93	2.23	2.58	2.56	-2.43	-5.12	-4.88	-4.49
	5.0	P & B	23.97	16.32	9.83	4.96	3.84	1.86	1.73	1.68	1.24
		T & B	-3.62	-2.07	-0.49	0.82	1.08	0.98	-0.87	-2.67	-2.65
		Svac.	5.90	6.69	7.64	8.53	8.63	8.91	4.51	-0.86	-2.04
12.9	1.2	P & B	-3.93	-3.88	-2.49	-0.38	0.26	1.42	0.13	-4.88	-7.30
		T & B	-7.77	-3.09	0.05	0.54	0.15	-1.70	-2.83	-2.43	-1.96
		Svac.	-29.69	-28.56	-26.17	-22.71	-21.56	-21.54	-15.84	-10.44	-8.93
	2.0	P & B	33.24	23.29	15.39	10.14	9.08	7.24	4.67	-3.34	-7.49
		T & B	-7.33	-3.52	-0.36	1.40	1.60	1.16	-0.47	-1.97	-2.09
		Svac.	-7.71	-8.84	-9.96	-11.11	-11.65	-21.36	-24.04	-20.10	-18.20
	5.0	P & B	46.15	32.97	21.92	13.64	11.69	8.01	7.07	5.57	4.05
		T & B	-10.65	-7.83	-5.31	-3.70	-3.47	-3.83	-5.48	-7.37	-7.92
		Svac.	17.98	19.80	21.78	23.17	23.04	29.57	7.17	-12.40	-15.36

TABLE IV
EFFECTIVE DIELECTRIC CONSTANT FOR INVERTED MICROSTRIP

Er	h2/h \ w/h	0.1	0.2	0.4	0.8	1.0	2.0	4.0	8.0	10
3.78	1.2	1.5634	1.4735	1.3731	1.2738	1.2442	1.1633	1.1012	1.0588	1.0488
	2.0	1.8952	1.8248	1.7326	1.6115	1.5659	1.4112	1.2647	1.1557	1.1295
	5.0	2.0410	1.9868	1.9136	1.8125	1.7724	1.6240	1.4528	1.2899	1.2447
	inf.	2.0827	2.0339	1.9675	1.8752	1.8385	1.7024	1.5453	1.3928	1.3484
12.9	1.2	2.5744	2.3117	2.0349	1.7668	1.6864	1.4635	1.2895	1.1686	1.1398
	2.0	3.8471	3.5509	3.1965	2.7768	2.6293	2.1595	1.7412	1.4364	1.3632
	5.0	4.7014	4.4330	4.0950	3.6658	3.5059	2.9514	2.3671	1.8529	1.7163
	inf.	5.1428	4.9043	4.5966	4.1947	4.0419	3.5010	2.9123	2.3646	2.2082

of w/h beyond its claimed range of validity, for both $\epsilon_r = 3.78$ and 12.9. It is interesting to note that while this model does not claim to be accurate for h_1/h values less than 0.4, for $\epsilon_r = 3.78$, $h_1/h = 0.2$ and $w/h \leq 2$, the accuracy is better than 1.58%.

Both P&B and T&B models are not valid for the limiting cases of $h_1/h = 0$ (regular microstrip) and $h_1/h = 1$ (no dielectric).

The Svacina model does not seem to be very accurate for any particular set of parameters, although it does seem to do a better job for large values of w/h and small values of ϵ_r. An exception to this statement is illustrated by the results for $\epsilon_r = 3.78$ and $h_1/h = 0.2$. For this case, the Svacina model is more accurate than the other models with an average error of 3.3% over the range $0.1 \leq w/h \leq 10$.

B. Inverted Microstrip

The effective dielectric constant for IM, as computed using these three methods, is compared to the exact theoretical value in Table III. The models are compared over the parameter ranges $0.1 \leq w/h \leq 10$, $1.2 \leq h_2/h \leq 5$ and $\epsilon_r = 3.78$ and 12.9. The exact theoretical values for IM are summarized in Table IV.

For $\epsilon_r = 3.78$, over its limited parameter range ($1 \leq w/h \leq 8$ and $1.2 \leq h_2/h \leq 2$), the P&B model exhibits an average error of 0.76% and a maximum error of 1.87%. For $\epsilon_r = 12.9$, the error increases with h_2/h since this model is not valid for $\epsilon_r > 6$.

For $\epsilon_r = 3.78$, the T&B model demonstrates very good accuracy (less than 1%) over its wider range of convergence ($.5 \leq w/h \leq 10$ and $1.05 \leq h_2/h \leq 2.5$). It is even quite accurate (less than 1.64% error) for values of w/h down to 0.1. Surprisingly, it is also accurate (less than 1.08% error) for $h_2/h = 5$ (outside of its claimed convergence range) if w/h is restricted to the range $0.4 \leq w/h \leq 4$. For $\epsilon_r = 12.9$, the T&B model degrades somewhat to a maximum error of 2.83% over its convergence range.

Both P&B and T&B models are not valid for the limiting cases of $h_2/h = 1$ (air-filled microstrip) and $h_2/h \to \infty$.

The Svacina model is not very accurate for any set of parameters, although it seems to improve for $\epsilon_r = 3.78$ and $h_2/h \to 1$.

III. New Models

Based on Wheeler's conformal mapping, Svacina has developed an interesting set of equations for the effective dielectric constant of SM and IM. While not very accurate, these expressions hold the promise of providing the mathematical functions, which if properly modified, may yield useful CAD formulas. To this end, we have modified Svacina's formulas by, first of all, insuring convergence for the extreme values of h_1 and h_2, and secondly, by fitting the remaining expressions to the exact theoretical data. The new models are summarized in the following sections.

A. Suspended Microstrip

For the case of SM, we define the following normalized variables as

$$x = h_1/h$$
$$u = w/h$$
$$E = \epsilon_{r2}/\epsilon_{r1}.$$

For $w/h > 1$, the filling factors are given by

$$q_1 = f_1\{1 - 0.6523/u_1 \ln[1.801 u_1 \sin(\phi)/x + f_2 \cos(\phi)]\}$$
$$q_2 = 1 - q_1 - q_w$$

where u_1 is the normalized effective line width given by

$$u_1 = w_{\text{eff}}/h = u + 2/\pi \ln[17.08(u/2 + 0.92)] \qquad (2)$$

q_w is Wheeler's filling factor for wide lines

$$q_w = 0.6523/u_1 \ln(1.801 u_1) \qquad (3)$$

and

$$\phi = \frac{\pi}{2}x$$
$$f_1 = x^{(0.8605+0.3491/E)}$$
$$f_2 = (1.929 + 5.908/E)u_1^{\alpha}$$
$$\alpha = (1.208 + 0.1077E) \cdot (u/4)^{(0.3048(0.5-x))}.$$

For $w/h \leq 1$, the filling factors are

$$q_1 = q_n\{1 - [2/\pi \cos^{-1}(x f_1)]^{f2}\}$$
$$q_2 = q_n - q_1$$

where q_n is Wheeler's filling factor for narrow lines given by

$$q_n = 1/2 + 0.26144/\ln(8/u) \cdot (1 + 0.2855 E_{12}^{-0.7517})$$

and

$$E_{12} = x(\epsilon_{r1} - \epsilon_{r2}) + \epsilon_{r2}$$
$$f1 = [u_1/2\,(1 + x)/(1 - x + u_1)]^{0.3915}$$
$$u_1 = (0.13955 + 0.8095/E)(0.0538 + 0.597u + 0.5624u^2)$$
$$f_2 = [1.677 + 0.7848/E - (1.4021 + 0.06055E) \cdot x + (0.7954 + 0.04382E) \cdot x^2] \cdot (u/0.4)^{[0\ 07(x-0.5)]}$$

Based on the above filling factors, the effective permittivity for suspended microstrip, is given by [13] as

$$\epsilon_{\text{eff}} = 1 - q_1 - q_2 + \epsilon_{r1}\epsilon_{r2}(q_1 + q_2)^2/(\epsilon_{r1}q_2 + \epsilon_{r2}q_1)$$

B. Inverted Microstrip

For the case of IM, we define the following normalized variables as

$$u = w/h$$
$$x = 1 - h/h_2$$
$$x_1 = 1 - x$$
$$E = \epsilon_{r2}/\epsilon_{r1}.$$

For $w/h > 1$, the filling factors are given by

$$q_1 = 1 - q_w f_1$$
$$q_2 = 1 - q_1 - q_3$$
$$q_3 = 0.6523(1 - f_2)/u_1 \ln[u_1 \cos(\phi)/(0.5552 + f_2 \cdot f_3) + \sin(\phi)]$$

where u_1 is the normalized effective line width given by (2), q_w is Wheeler's filling factor for wide lines given by (3) and

$$f_1 = 1 - 0.06078[1 - \cos(\pi x^{1/2})] \cdot [1 - 0.3206/u_1 - 2.3188/u_1^3] \cdot E^{0.4356}$$
$$f_2 = x^{\alpha}$$
$$\alpha = 0.4746 + 1.3778/E - (0.1376 + 0.00945E)x + 0.6153x^3$$
$$\phi = \frac{\pi}{2} f_2$$
$$f_3 = (3.9717 + 8.0922/E)u_1^{-(0\ 1321+1.3907/E)}.$$

For $w/h \leq 1$, the filling factors are given by

$$q_1 = 1/2 + (q_n - 1/2)f_1$$
$$q_2 = 1 - q_1 - q_3$$
$$q_3 = (f_2 - f_3)/[\pi \ln(8/u)]$$

where q_n is Wheeler's filling factor for narrow lines

$$q_n = 1/2 + 0.26144/\ln(8/u) \cdot (1 + 0.2855\epsilon_{r1}^{-0.7517})$$

and

$$f_1 = 1 + 0.1431[1 - \cos(\pi x)] \cdot [1 - 1.652/\ln(12.532/u)] \cdot E^{0.641}$$
$$f_2 = \ln(A)\cos^{-1}[(xA^{1/2})^{\alpha}]$$
$$A = (2 - x)/[x + u/4(1 - x)]$$
$$\alpha = [0.14695 + 1.657/E + (0.6386 + 0.7881/E) \cdot x] \cdot (2x_1)^{[0.3075(u-.4)]}$$
$$f_3 = 1.0558 x_1^{1.928}(u/0.4042)^{[x(0\ 30035+0.2096/E)]}.$$

Based on the above filling factors, the effective permittivity for inverted microstrip is given by [13] as

$$\epsilon_{\text{eff}} = \epsilon_{r1}q_1 + \epsilon_{r2}(1 - q_1)^2/(\epsilon_{r2}q_3 + q_2)$$

TABLE V
PERCENTAGE ERROR FOR SUSPENDED MICROSTRIP (NEW MODEL)

Er	h1/h \ w/h	0.1	0.2	0.4	0.8	1.0	2.0	4.0	8.0	10
3.78	0.0	0.17	0.10	-0.02	-0.11	-0.04	-0.41	-0.31	-0.22	-0.20
	0.2	0.12	0.19	-0.00	-0.11	0.03	-0.29	-0.07	-0.13	-0.21
	0.5	-0.10	0.02	-0.20	-0.05	0.31	-0.01	0.04	-0.07	-0.15
	0.8	-0.44	-0.04	0.00	0.22	0.52	-0.19	-0.10	-0.25	-0.31
12.9	0.0	0.40	0.28	0.05	-0.22	-0.22	0.31	0.26	0.17	0.14
	0.2	-0.25	0.12	-0.14	-0.32	-0.05	-0.85	0.55	-0.07	-0.65
	0.5	-0.10	0.26	-0.21	-0.19	0.34	-0.19	-0.14	-0.37	-0.59
	0.8	0.10	0.42	-0.22	-0.55	-0.16	-0.27	0.44	0.42	0.30

TABLE VI
PERCENTAGE ERROR FOR INVERTED MICROSTRIP (NEW MODEL)

Er	h2/h \ w/h	0.1	0.2	0.4	0.8	1.0	2.0	4.0	8.0	10
3.78	1.2	-0.71	-0.31	-0.01	-0.39	-0.76	0.05	-0.26	-0.32	-0.30
	2.0	-0.24	-0.01	0.11	-0.01	-0.13	-0.07	0.47	0.72	0.73
	5.0	-0.02	0.03	0.04	-0.08	-0.16	-1.02	-0.53	0.44	0.78
	inf	-0.00	0.03	0.09	0.01	-0.13	0.00	0.09	0.02	-0.03
12.9	1.2	-0.67	-0.36	-0.13	-0.13	-0.20	0.13	-0.34	-0.37	-0.32
	2.0	-0.37	0.09	0.05	-0.25	-0.02	0.40	0.42	0.15	0.05
	5.0	1.00	0.86	0.40	0.06	0.44	-0.73	-0.33	0.59	0.88
	inf	0.18	0.03	-0.13	-0.11	0.05	-0.14	0.09	0.07	-0.03

C. Results

Based on these equations, the effective dielectric constant for SM is compared to the exact theoretical value in Table V. The results are compared for $0.1 \leq w/h \leq 10$, $0 \leq h_1/h \leq 0.8$ and two different values of dielectric constant, 3.78 and 12.9. For $\epsilon_r = 3.78$, the worst case error is 0.52% and is typically better than 0.2%. For $\epsilon_r = 12.9$, the worst case error is 0.65% and is typically better than 0.35%. As opposed to the previous models, the new model is valid and converges uniformly in both limits, $h_1/h = 0$ and $h_1/h = 1$. The case of $h_1/h = 1$ is not tabulated since it produces the trivial result, $\epsilon_{\text{eff}} = 1$. While trivial, the new model produces this result correctly and should be accurate for h_1/h values approaching this limiting case.

The model results for IM are summarized in Table VI. The model is compared to theoretical values for $0.1 \leq w/h \leq 10$, $1.2 \leq h_2/h < \infty$ and two different values of dielectric constant, 3.78 and 12.9. For $\epsilon_r = 3.78$, the worst case error is 1.02% and is typically better than 0.5%. For $\epsilon_r = 12.9$, the worst case error is 1.00% and is typically better than 0.4%. As opposed to the previous models, the new model isvalid and converges uniformly in both limits, $h_2/h = 1.0$ and $h_2/h \to \infty$. The case of $h_2/h = 1.0$ is not tabulated since again it produces the trivial result $\epsilon_{\text{eff}} = 1$. While trivial, the new model produces this result correctly and should be accurate for h_2/h values approaching this limiting case.

While formulated and optimized for $\epsilon_r = 3.78$ and 12.9, the accuracy of this new model has been checked for $\epsilon_r = 10$ (alumina). For suspended microstrip and $h_1/h = 0.5$, these results indicate a worst case error of 2.1% at $w/h = 10$. Similarly, with inverted microstrip and $h_2/h = 2$, a worst case error of 1.3% also occurred for $w/h = 10$. In both cases, the error was generally below 1% for smaller values of w/h.

IV. CONCLUSION

The accuracies of suspended and inverted microstrip CAD models have been examined. While the P&B and T&B models are reasonably accurate over their claimed ranges, these ranges are quite limited. This is particularly true for the P&B model. Further, these models do not converge for the limiting cases of either complete substrate filling or a zero thickness substrate. While converging in some of these cases, the Svacina model is not particularly accurate for any set of microstrip parameters.

Based on Svacina's work, new CAD models for SM and IM have been developed. For quartz and GaAs dielectrics, these models have demonstrated accuracies of 1% or better over wide parameter ranges. This implies accuracies of 0.5% or better for the guide wavelength and the characteristic impedance. These results are significantly better than the best results of previous models. Further, the new models converge in the limiting cases of either complete substrate filling or a zero thickness substrate. This ensures better accuracy for model parameters near these limits. Finally, these new models consist of relatively simple analytical expressions which are well suited to the requirements of the CAD environment.

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J. M. Schellenberg (S'68–M'71–SM'94), photograph and biography not available at the time of publication.