The measured values in Fig. 8 support the predictions of the theory. The measurements were taken after calibrating the network analyzer through the coupled-ring model. A through-calibration reduces the mismatch effects due to the feed-to-ring transitions.

Several techniques could be used to alter the S_{21} performance of a ring network. Using a mismatched ring network with stub tuners on the feeds is one possible narrowband approach to reduce wow. Reactive tuning networks near the feed-to-ring transitions can improve the wow performance in a similar way. Changing the relative phase and amplitude errors between the feeds in a multiple feed network also has an effect on wow. The effects of each of these techniques could be investigated in more detail using the approach outlined in this paper.

IV. Summary and Conclusion

In this paper a theoretical model for the performance of a coupled-ring rotary joint was derived. We first considered the configuration of a single channel and described a coupled transmission line model for the coupled-ring network. We then determined the type of ring network necessary for a good match and low wow variations. A series of measurements on some test models support the theoretical results.

The even-mode impedance, Z_{0e}; the odd-mode impedance, Z_{0o}; and the feed spacing have a significant effect on the transmission coefficient, S_{21}, for the coupled-ring network. For feed spacings between 0.05λ and 0.15λ, values of $160\ \Omega < Z_{0e} < 360\ \Omega$ and $Z_{0o} < 2\ \Omega$ give S_{21} values better than -0.3 dB. The size of the S_{21} wow variations can be controlled by changing the spacing between the ring feeds. Feed spacings less than $\lambda/8$ allow relatively small values of wow.

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Computation of the Dispersion Characteristics of a Shielded Suspended Substrate Microstrip Line

I. P. Polichronakis and S. S. Kouris

***Abstract*—The dispersion characteristics of a shielded suspended substrate microstrip line are calculated using five different sets of basis functions for the current distributions. Their comparison leads to the more suitable basis functions for the acquisition of fast and accurate results for frequencies up to 100 GHz.**

I. Introduction

Shielded suspended substrate microstrip lines (SSL) have been widely discussed in connection with the millimeter-wave integrated circuits [1]. Their electrical characteristics have been obtained using various methods of analysis [2]–[4]. In this paper the characteristics of the dominant mode for frequencies up to the millimeter wave region are determined using spectral domain analysis (SDA).

It is known that in the spectral domain method the assessment of the best basis functions for the current components on the strip is of fundamental importance for the numerical efficiency of the method; but it is also important to keep the computation time small enough. For this purpose a) the number of basis functions to approximate the actual current densities on the strip and b) the number of spectral terms necessary and sufficient to obtain an accurate solution for the effective dielectric constant (ϵ_{eff}) and the characteristic impedance (Z_0) of the line, must be considered and optimized. For this reason a number of sets of basis functions, found in the literature, are examined and their results are compared in order to find out the more suitable one which should be employed in the analysis of SSL.

II. Basis Functions

The characteristics of the dominant mode of the SSL, i.e., the characteristic impedance Z_0 and the effective dielectric constant $\epsilon_{eff} = (\beta/k_0)$, β being the propagation constant and k_0 the free-space wavenumber, are evaluated using the SDA as it is presented by Itoh [5] and Knorr and Tufekciogloy [6]. The cross-section of the SSL is illustrated in Fig. 1. In this work it is assumed that the line is lossless and the strip thickness is negligible.

It is well known that various sets of basis functions have been employed in the analysis of the different types of striplines. For instance, Itoh and Mittra used a first order approximation with a sine function for the representation of J_x and a triangular function for J_z [7]. Jansen proposed a full set of basis functions that ensures the singular behaviour of the field for any degree of solution accuracy and possesses the physical property of the surface current density to be twice differentiable [8]. Leung and Valanis [9] in order to obtain microstrip dispersion characteristics used also a first order solution. They adopted for the J_x current component the expression proposed by Delinger [10] and for the J_z current component the expression proposed by Kobayashi [11]. Other authors

Manuscript received February 25, 1991; revised July 22, 1991.
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IEEE Log Number 9105441.

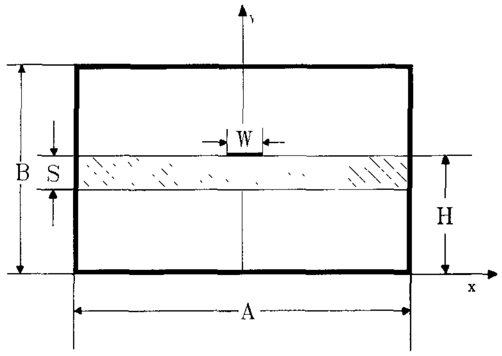


Fig. 1. Cross-section of the suspended substrate stripline (SSL). The outer dimensions of the waveguide are A and B; W is the strip width, S is the substrate thickness and H is the strip distance from the bottom side of the waveguide.

TABLE I
SETS OF BASIS FUNCTIONS UNDER TEST

Set	Transverse Current Component		Longitudinal Current Component	
1	0		$J_z = [1 - (2x/w)^2]^{-1/2}$	[8]
2	$J_x = a_1 * (2/w) * \sin(2\pi x/w)$	[7]	$J_z = [1 + \|2x/w\|^3]$	[7]
3	$J_x = a_1 * \begin{cases} \sin(k_x) & \|x\| < w/2 \\ \cos(k_x) & 0.4w < \|x\| < w/2 \end{cases}$		$J_z = 1 + 10\left[1 - \frac{2x_c}{W}\right]\frac{M(x) - 1}{M(x_c) - 1}$	
	$k_x = (\pi x/0.8w)$	[10]	where $M(x) = [1 - (2x/w)^2]^{-1/2}$	[11]
4	$J_x = a_1 * \int_0^{(2x/w)} \frac{[\cos(v - J_0(\pi)]}{[1 - v^2]^{1/2}} dv$	[8]	$J_z = \frac{b_1 + [\cos(2\pi x/w) - J_0(\pi)]}{[1 - (2x/w)^2]^{1/2}}$	[8]
5	$J_x = a_1 * \frac{\sin(2\pi x/w)}{[1 - (2x/w)^2]^{1/2}}$	[12]	$J_z = \frac{\cos(2\pi x/w)}{[1 - (2x/w)^2]^{1/2}}$	[12]

Note:
J_0 is the zero order Bessel function of the first kind.
The value of x_c for the evaluation of J_z in set 3 is shown in Fig. 5 at [11].

employed a set of sinusoidal functions modified by an "edge condition" term [12].

Therefore, if one of the previously mentioned sets is to be adopted for the analysis of SSL, it is necessary to compare all of them and find out which one could keep the computation simple, fast, and accurate. For this purpose five different sets of basis functions have been compared. They are:

1) A zero order solution obtained using the set proposed in [8] with $M = N = 1$.

2) A first order solution using the functions proposed in [7].

3) A first order solution using the set proposed in [9].

4) A second order solution using the set proposed in [8] with $M = N = 2$.

5) A first order solution using modified sinusoidal functions with $M = N = 1$ [12].

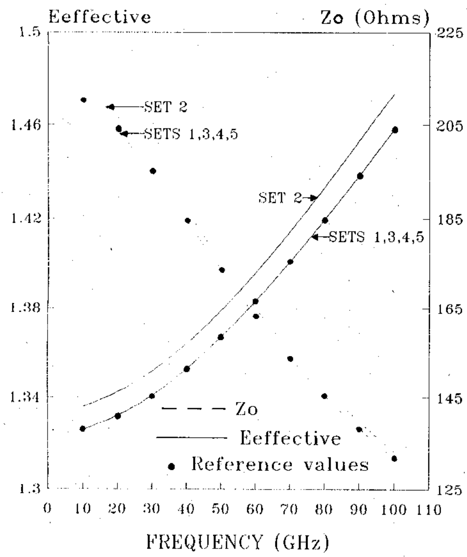
These trial functions for the current distributions are reported in Table I along with their Fourier transformations. All of them lead to a characteristic matrix of low order and thus to a fast computation procedure.

The comparison is made with respect to a reference value for the effective dielectric constant ϵ_{eff} and the characteristic impedance Z_0. This value is obtained using a large number of basis functions that, thus, may lead to an optimum representation of the actual current densities on the strip. Kobayashi [13] showed that, when five basis functions are employed for each current component, the approach has a very high degree of accuracy. For this purpose the Jansen's set of basis functions as well as the set of modified sinusoidal functions is used with five basis functions for each current component and 500 spectral terms. The results obtained from the two sets show a difference, for both the ϵ_{eff} and Z_0, less than 0.01%. Therefore, the values evaluated from one set or the other can be used as reference values to compare all the different sets of basis functions in Table I.

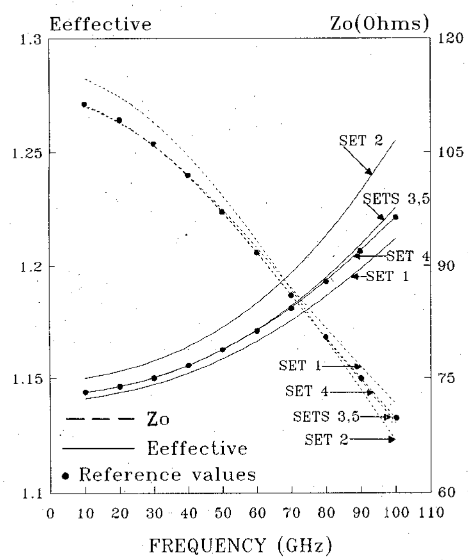
III. Numerical Results

The dispersion characteristics of a SSL are calculated using the sets of basis functions reported in Table I. It is assumed that the line is placed in a WR-28 shielding with a centered dielectric substrate of relative dielectric constant $\epsilon_r = 3.0$ and of thickness $S = 0.125$ mm. A narrow strip having width $W = 0.15$ mm (Fig. 2(a)) and a wider strip with $W = 1.25$ mm (Fig. 2(b)) are examined.

Fig. 2 shows the dispersion characteristics, effective dielectric constant $\epsilon_{\text{eff}} = (\beta/k_0)^2$ and characteristic impedance Z_0 of the dominant mode, obtained using 500 spectral terms. It can be seen from this figure that the set of basis functions number 2 in Table I, for both cases of strip width, gives higher values of ϵ_{eff} compared to the reference values and consequently it yields an associated error of the same order in the characteristic impedance Z_0. This error is about 2% to 3% respect to the reference values. Therefore, it is

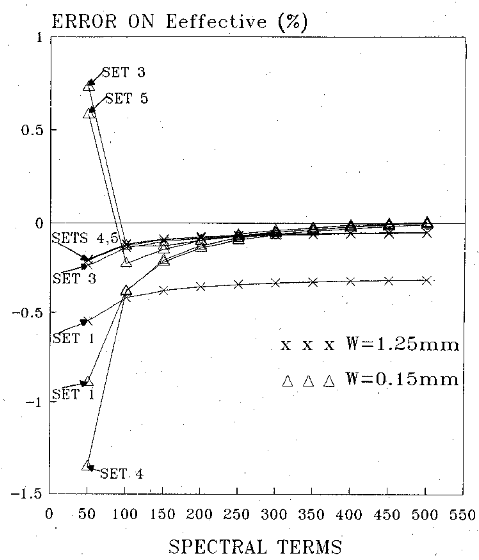


(a)

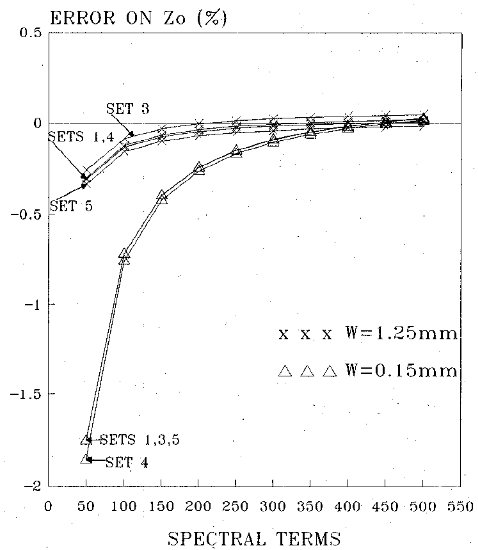


(b)

Fig. 2. Dispersion characteristics of SSL for various basis functions (WR-28 shielding, S = 0.125 mm, H = 1.7155 mm, ϵ_r = 3.0). (a) W = 0.15 mm. (b) W = 1.25 mm.



(a)



(b)

Fig. 3. Convergence behavior of (a) $\epsilon_{\text{effective}}$ and (b) Z_0 for different strip widths and various basis functions. (WR-28 shielding, S = 0.125 mm, H = 1.7155 mm, ϵ_r = 3.0).

concluded that this set of functions is unacceptable for an accurate analysis of a SSL. The dispersion characteristics for the other sets of basis functions are very satisfactory when the strip is narrow (Fig. 2(a)). For a wider strip (Fig. 2(b)) the set of functions number 1, i.e., the zero order approximation yields an error for ϵ_{eff} of 0.3% at 10 GHz and up to 1% at 100 GHz. The corresponding error on Z_0 is 0.2% and 3%, respectively. This means that the longitudinal current component becomes absolutely essential for frequencies up to the millimeter-wave region. Therefore, the zero order solution is unacceptable.

Furthermore, it is evident from Fig. 2 that the sets of functions number 3 and 5 lead to an error of 0.2% at 100 GHz. On the other hand the set of functions number 4 gives highly accurate results compared to the reference values, leading to an error less than 0.1% for all the frequencies up to 100 GHz. It must be noted however, that if an accuracy better than 0.5% for all the frequencies up to 100 GHz could be accepted, then the sets of functions 3 and 5 are also appropriate for any analysis of this line. These sets also lead to a characteristic matrix of order two, while the set of functions 4 gives a matrix of order three. This means that if the set of functions 3 and 5 is used instead of set 4, the computation time is reduced to half.

Another criterion for the choice of the basis functions is the convergence behavior of the solutions. Fig. 3 illustrates the convergence behavior of the relative dielectric constant ϵ_{eff} (Fig. 3(a)) and of the characteristic impedance Z_0 (Fig. 3(b)) at a frequency of 30 GHz for all the tested sets of basis functions except for the set number 2. The narrow strip-width (W/A = 0.022) as well as the wider strip-width (W/A = 0.176) case is also examined here. Fig. 3 shows that for all the tested sets, the convergence of the solutions of ϵ_{eff} is faster than that of the characteristic impedance. Therefore, a larger number of spectral terms is required for the accurate computation of Z_0. From the same figure it becomes evident that the number of spectral terms necessary to obtain a certain accuracy in the values of ϵ_{eff} and Z_0 is higher in the case of a narrow strip than in the case of a wider one. Indeed, Fig. 3 shows clearly that for

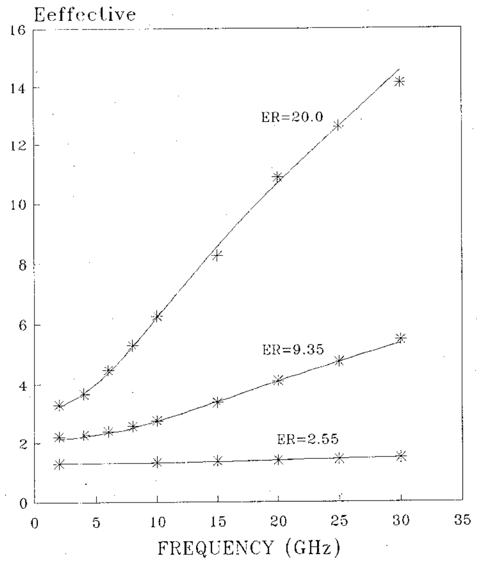


Fig. 4. Effective dielectric constant versus frequency for different dielectric substrates. Solid lines show results obtained with SDA, whereas asterisks are Yamashita's results [2].

narrow strips the number of spectral terms necessary to obtain an accuracy of 0.1% in both ϵ_{eff} and Z_0, is of the order of at least 250 terms for the effective dielectric constant and 350 terms for the characteristic impedance. On the contrary, for wider strips the number of only 150 spectral terms ensures the same order of accuracy (0.1%) for both ϵ_{eff} and Z_0. Now, it is worth noting the behavior of the solution for ϵ_{eff}, which is obtained using the set numbered 1 in Table I. In the case of wide strips it converges to a value that deviates from the reference one by about 0.3%. This behavior states the fact that even at the lower frequencies of the millimeter-wave band the zero order approximation leads to an error in the computation of ϵ_{eff} when wider strips are considered.

Finally, in order to evaluate the accuracy of our analysis and the proper functioning of the computing program, a comparison is made between our results and those found by Yamashita [2] for frequencies up to 30 GHz. It is assumed that the suspended substrate microstrip line is placed in a shielding with outer dimensions $A = 20$ mm and $B = 10$ mm. The strip width is 2 mm, and the dielectric substrate has a thickness of 1 mm. Three different dielectric substrates are considered, that is, three different dielectric constants: $\epsilon_r = 2.55$, $\epsilon_r = 9.35$ and $\epsilon_r = 20$, respectively. The results, as shown in Fig. 4, are obtained using the set of basis functions number 4 in Table I with 350 spectral terms. In the same figure the results obtained by Yamashita [2], who employed the method of non-uniform discretization of integral equations, are also shown. Clearly, a good agreement exists between our results and those reported by Yamashita.

IV. Conclusion

The comparison of various basis functions that can be used in the study of the shielded suspended substrate microstrip lines, and the convergence behavior of their solutions have shown that the longitudinal current component on the strip is essential for an accurate analysis of these lines, especially in the millimeter-wave region. It is concluded that the set of basis functions number 4 in Table I should be used in order to obtain fast and accurate results. However, the sets 3 and 5 may be also used if less accuracy is acceptable.

Acknowledgment

During this research I. P. Polichronakis was holder of an I.K.Y. scholarship and he would like to express his gratitude to I.K.Y.

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18–42 GHz Experimental Verification of Microstrip Coupler and Open End Capacitance Models

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***Abstract*—A cavity resonance technique is used to experimentally verify microstrip coupler and open end capacitance models over the frequency range 18–42 GHz. In addition, these results are confirmed using an alternative version of the technique which directly determines**

Manuscript received June 24, 1991; revised November 7, 1991.
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IEEE Log Number 9105702.

0018-9480/92$03.00