Short Papers

Characteristic Impedance of Integrated Circuit Bond Wires

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Abstract—**In microwave circuit analysis, bond wires are frequently modeled as lumped elements or sections of microstrip. These models are insufficient since part of the wire is suspended above the substrate. This paper shows numerical results that provide the line impedance and effective dielectric constant for a round wire above a grounded dielectric substrate.**

I. Introduction

In many microwave engineering circuit problems, circular bond wires are often modeled as flat microstrip lines of similar horizontal dimensions or even as lumped elements such as inductors. These models are suitable for wires that are very short when compared to a wavelength. As the frequency is increased, however, these "short" bond wires can be a significant fraction of a wavelength and exhibit transmission-line properties, and quantities such as the line impedance Z_0 and the effective dielectric constant ϵ_{eff} become important. The low-frequency models are especially deficient when the bond wire bridges two lines or components, such as in Lange couplers or in bonding transistors to biasing and other structures. In these cases, the wire spans the gap in air, creating variations in the effective dielectric constant, line impedance, and line wavelength. Here, Z_0 and ϵ_{eff} become functions of the geometry of the bonding structure as well as the wire and substrate size, thereby leading to possible inaccuracies when other models are assumed. Relationships that describe the line impedance and effective dielectric constant for the wire–air–substrate structure shown in Fig. 1 are therefore necessary. This structure may be thought of as an idealized bond wire.

A full-wave analysis of the structure shown in Fig. 1 has been done under the very strict assumption that the wire is far removed from the substrate [1]. In microwave integrated circuits, however, these wires may be located on the substrate or a few wire radii above it, so the results of the above-mentioned authors are not directly applicable. By assuming a strictly TEM propagation mode, electrostatic field analysis can be used to find Z_0 and ϵ_{eff} of the wire–air–substrate structure if the capacitance of the structure (with and without the nonunity dielectric) and the line impedance in the presence of a unity dielectric can be found [2]. The specific equations that need to be solved are

$$\epsilon_{\text{eff}} = C(\epsilon_r)/C(1) \tag{1}$$

and

$$Z_0 = Z_0'/(\epsilon_{\text{eff}})^{0.5} \tag{2}$$

where $C(1)$ is the capacitance in the presence of a unity dielectric, $C(\epsilon_r)$ is the capacitance in the presence of a nonunity dielectric, and Z_0' is the line impedance in the presence of a unity dielectric. This particular approach lends itself particularly well to computer-based solutions of the electrostatic field equations using techniques such as the network analog approach outlined by Lennartsson [3]. In calculating the transmission-line properties using this numerical technique, a shielded line structure is generally considered. Unshielded line can be approximated as a shielded one with the shield far removed from the strips or wires. An alternative approach to calculating the line parameters of unshielded lines is to employ the principles of conformal mapping in transforming the unshielded structure into a shielded one, and then applying Lennartsson's numerical analysis to the modified line. The following is a discussion of this approach and a presentation of the transmission-line properties of the wire–air–dielectric line.

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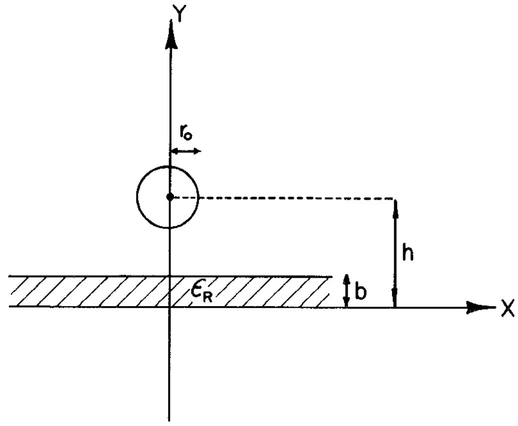

Fig. 1. The geometry of the wire–air–substrate transmission line.

II. Coordinate Transformation

The structure shown in Fig. 1 shows a wire of radius r_0 at a height h above ground, with a nonunity dielectric (ϵ_r) of thickness b in contact with ground. The ground and dielectric are considered infinite in extent. Through the use of conformal mapping and the appropriate coordinate transformation, the substrate boundary, ground, and wire in the $x-y$ plane can be transformed into closed circles in the $u-v$ plane [4]. By choosing the bilinear transformation

$$w = u + jv = (z - jh)/(z + jh) \qquad z = x + jy \tag{3}$$

and applying it to the transmission line shown in Fig. 1, an offset coaxial structure with nonuniform dielectric (Fig. 2) is obtained, where the transformed circle radii and coordinates are defined as follows:

$$\begin{aligned} u_0 &= b/(b+h) \\ u_1 &= 1\Big/\left[(2h/r_0)^2 - 1\right] \\ R_0 &= h/(h+b) \\ R_1 &= 2/\left[(4h/r_0) - (r_0/h)\right]. \end{aligned} \tag{4}$$

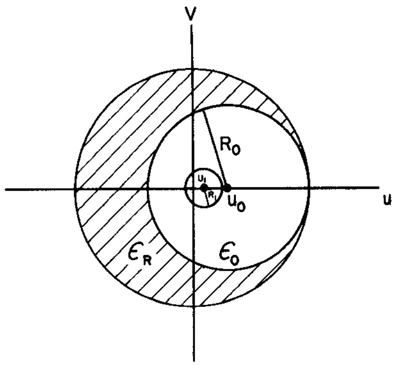

Fig. 2. The modified transmission line resulting from a conformal mapping of the wire–air–substrate line.

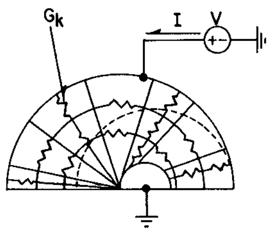

Fig. 3. A network analog of the modified wire–air–substrate transmission line of Fig. 2.

These points and radii are indicated in Fig. 2.

The line impedance of the structure shown in Fig. 2 is [5], [6]

$$Z_0' = 60\cosh^{-1}\left[\left(1-u_1^2\right)/(2R_1)+R_1/2)\right] \quad (5)$$

if a unity dielectric is assumed throughout.

By computing the capacitance of the offset coaxial structure, both with and without the dielectric ϵ_r, the desired transmission-line parameters for the idealized bond wire can be found.

III. Calculation of Effective Dielectric Constant

In Lennartsson's technique [3], the continuous structure under study is approximated by a finite network array of resistors (Fig. 3). For a network analog of the structure shown in Fig. 3, the conductivity of a particular element corresponds to the permittivity of that element [7]

$$\sigma_k = \epsilon_k. \quad (6)$$

The values of conductance G_k in the network are functions of the geometry of the particular element as well as the conductivity of the element. The effective dielectric constant is computed as follows. Two networks of conductances G_k are constructed, one with two dielectrics as in Fig. 2, the other with $\epsilon_r = 1$ throughout. Once the network has been established, a potential source V (Fig. 3) is impressed on each network, resulting in current being drawn from the source. The value of this current for each network is computed using a network equation program such as SPICE [8]. The current drawn by the network with two dielectrics is called I_2, the current for the single dielectric network is I_1. The effective dielectric constant is then the ratio of these two currents

$$\epsilon_{\text{eff}} = G_2/G_1 = I_2/I_1. \quad (7)$$

An array of 100 resistive elements was used in this analysis.

IV. Discussion

The line impedance and effective dielectric constant of a wire above an alumnia substrate ($\epsilon_r = 9.6$) will now be discussed. The

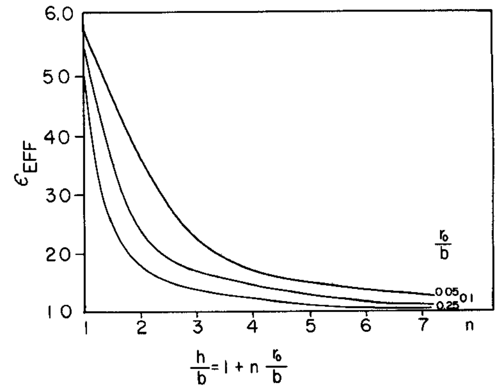

Fig. 4. Plot of the effective dielectric constant versus height above ground for various values of the parameter r_0/b.

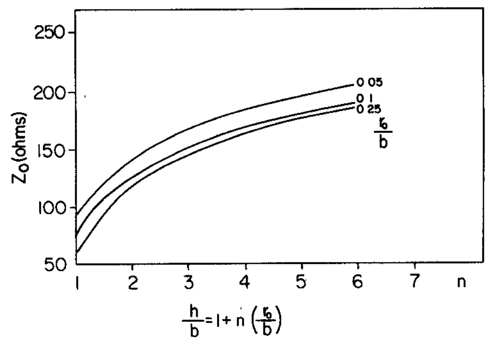

Fig. 5. Plot of the characteristic line impedance versus height above ground for various values of the parameter r_0/b.

transmission-line properties of this structure have been computed using (1)–(7) and the results are illustrated in Figs. 4 and 5. The line impedance and effective dielectric constant for increasing heights above the substrate (nr_0/b) are shown in the figures. Note that in Fig. 4, the effective dielectric constant decreases as the distance from the substrate increases, indicating the diminishing effects of the dielectric substrate. The model also shows that for weak dielectrics ($\epsilon_r - 1 \ll 1$), the effective dielectric constant approaches $(\epsilon_r)^{0.5}$, in agreement with values derived by other authors [9], [10]. Good agreement is indicated when compared with the quasi-TEM approximation of Kuester and Chang [1] for the wire far removed from the substrate. An estimate of the error introduced in the calculation of the effective dielectric constant can be found by inspection of Kuester and Chang's [1] approximation for the effective dielectric constant, repeated here for convenience

$$\epsilon_{\text{eff}} = \frac{\ln[2h/r_0]}{\ln[2(h-b)/r_0 + 2b/r_0\epsilon_r]}. \quad (8)$$

For transmission-line structure parameters $r_0/b = 0.05$ and $h/b = 1.35$, $\epsilon_{\text{eff}} = 1.37$. These same structure parameters show an effective dielectric constant of 1.4 using the model presented here. The error between the model and the quasi-TEM approximation of (8) is 2 percent, in agreement with Lennartsson's [3] error estimates.

A comparison with microstrip line will now be presented. From Fig. 5, the line impedance for a wire of radius $r_0/b = 0.05$ (corresponding to a 25-μm radius bond wire and a 500-μm-thick alumina substrate, for example) in contact with the substrate is shown to be 93 Ω and the effective dielectric constant is 5.8. Using a microstrip model for this bond wire and assuming a shape ratio of $w/h = 0.05$ $(2r_0/b)$, the line impedance is approximately 109 Ω and the effective dielectric constant is 5.3 [2]. The computed dielectric constant includes the effect of finite strip thickness.

V. Conclusions

An analysis of an idealized bond wire structure based on conformal mapping and a numerical method for calculating the TEM parameters has been presented. This model allows the TEM properties of a wire transmission line to be computed, rather than assuming the wire is a lumped inductance or approximating the wire line as rectangular microstrip. Also, the TEM properties of the wire suspended above the substrate can be computed. This allows more accurate analysis of microwave systems containing wire lines.

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