SPECTRAL-DOMAIN ANALYSIS OF COMPLEX CHARACTERISTIC IMPEDANCE OF A LEAKY CONDUCTOR-BACKED SLOTLINE

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ABSTRACT: We define an "equivalent complex characteristic impedance" for a conductor-backed slotline, that can be useful for circuit modeling purposes. Standard methods for computing the characteristic impedance of non-leaky transmission lines would not apply to a conductor-backed slotline due to its non-standard leakage behavior. Two alternate methods are proposed, that are compared with each other, as well as validated by comparing with rigorous 3D simulations of a practical circuit geometry.

INTRODUCTION: Though the leakage mechanism in certain types of printed transmission lines have been recognized for sometime [1] - [4], only the propagation behavior of such leaky lines have been investigated. The impedance characteristics of leaky lines have not been studied. It is possible to design novel practical circuits such as couplers, antenna feeds, signal transitions, etc., that make novel use of the power leakage concept in printed lines. For such circuit applications, it is important to define a characteristic impedance, Z_c, for an ideal infinite-length leaky line, that can be useful for simple circuit modeling of practical finite-length sections. Unfortunately, the standard definitions of characteristic impedance commonly used for non-leaky transmission lines would not apply when leakage exists. For a leaky conductor-backed slotline (CBS), for example, defining an "equivalent characteristic impedance" is made complicated due to its non- conventional growing fields. Due to indefinite growing nature of the transverse fields of a CBS, which increase to infinity at large distances, the total cross-sectional power for a given slot voltage would become infinitely large. Therefore, a standard power-voltage definition [$Z_c =$ (voltage)^2/(cross-sectional power),] of the characteristic impedance, commonly used for regular slotlines, can not be used here. This will result in a trivial zero value of the characteristic impedance, which is not practically meaningful. The voltage-current definition ($Z_c =$ voltage between the two conductors / the total current) will also fail to work, because the total current on the groundplane of a CBS can not be properly defined.

THEORY: In this paper we will present two definitions for the characteristic impedance of a conductor-backed slotline (CBS.) The geometry of a CBS, which is known to be leaky at all frequencies [1,2], is shown in Fig.1. A simple quasi-static distributed model for a general leaky transmission line is shown in Fig.2, that includes material as well as leakage loss. For a CBS, particularly, the leakage loss is a distributed radiation process that can be modeled as distributed shunt conductance, G'. Similarly, for a leaky strip-type transmission line the leakage loss can be incorporated via distributed series resistance, R'. The total fields of the transmission line of Fig.2 consists of two parts: (1) the radiation fields produced due to the distributed radiating elements, that are exponentially growing in transverse directions, and (2) the quasistatic transmission line fields.

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The quasistatic transmission line fields are bound to the vicinity of the transmission line, and dictate the characteristic impedance of the line. Whereas, the exponentially growing radiation fields from the distributed sources are a part of the loss process that do not directly contribute to the power transmission along the transmission line (the effect of radiation is indirectly accounted for through the distributed radiation resistance R' or conductance G'.) We analytically extract out the exponentially growing leakage fields from the total fields of a CBS. This is implemented using a residue theory on the complex spectral plane [2]. The rest of the fields are called the "bound-mode fields." The transverse power associated with these bound-mode fields is then calculated by integrating over the transverse plane. We now define a characteristic impedance using the bound-mode power, P_b:

$$Z_c = \frac{P_b^*}{|V|^2}. \tag{1}$$

This characteristic impedance, referred to as the "bound-mode characteristic impedance," is expected to be valid for circuit modeling purposes. It may be noted, the characteristic impedance obtained above is a complex number, unlike the purely real number for a non-leaky, lossless transmission line.

We also propose an alternate method based on a simple transmission line theory of Fig.2. First, the radiation conductance, G', can be analytically obtained by calculating the power radiated away by the leakage fields. Using spectral domain Green's functions and residue calculus, and assuming a uniform field across the slot width, W, it can be shown,

$$G' = \frac{\varphi_p}{2d\omega\mu_0}\left(\frac{\sin(\varphi_p W/2)}{\varphi_p W/2}\right)^2, \tag{2}$$

$$\varphi_p = \sqrt{k_0^2\epsilon_r - k_e^2};\ \ \mathrm{Im}(\varphi_p) > 0, \tag{3}$$

where $k_e = \beta - j\alpha$ is the complex propagation constant of the CBS obtained separately using [2], and ω is the frequency of operation in rad/s. From the known values of G' and k_e, we can find the values of the circuit parameters L, C, and Z_c of Fig.1 using transmission line theory:

$$Z_c = \frac{|\mathrm{Im}(k_e^2))|}{k_e G'}. \tag{4}$$

We refer to this method as the circuit extraction method. Though the method is based on a quasistatic model of the transmission line, it should provide a first order approximation for comparison with the more rigorous definition obtained earlier in (1).

We have also performed 3D electromagnetic simulations of a realistic circuit geometry in order to validate the characteristic impedance definitions proposed. A finite-length section of a short-circuited CBS stub of length $L = 20\lambda_0$, excited at the center by a shunt current source (see Fig.3 inset,), is used for the simulation. The numerical simulation of the above circuit geometry is separately performed using a full-wave method of moments. The characteristic impedance of the line is derived from the input impedance, Z_{in}, seen by the excitation source:

$$Z_c = \frac{2Z_{in}}{j\tan(k_e L/2)} \tag{5}$$

RESULTS: Fig.3 and Fig.4 show comparison of characteristic impedance values obtained using (1,4,5), for different substrate thicknesses, d, and substrate dielectric constant, ϵ_r, respectively. More 3D simulations have been done with different stub lengths and source positioning, showing consistent results. It may be noted here, that the imaginary parts of the characteristic impedance, which have much smaller magnitudes compared to the real parts, could not be derived properly from the 3D simulations. This is because, the additional reactive impedance usually seen at the input discontinuity masks the much smaller reactive values contributed by the transmission line characteristic impedance. The independent results of Fig.3 and Fig.4 are seen to agree well, which should validate the proposed definitions. In Fig.3, the characteristic impedance is zero for $d = 0$, which is due to the short circuiting effect of the bottom ground plane, and increases with d. For large values of d, the parallel plate mode excitation is reduced, which explains the decrease of the imaginary part of Z_c and the leakage constant α. In Fig.4, when $\epsilon_r = 1.0$, the geometry turns into a TEM structure with no leakage, and hence a purely real value of Z_c.

CONCLUSIONS: As we conclude from our investigation, the new definitions of characteristic impedance should be used for circuit designs of transmission lines that are predominantly leaky. The basic theory can be similarly extended to other slot- and strip-type transmission lines. The bound-mode impedance definition is inherently more rigorous than the circuit extraction method. However, the circuit extraction method is analytically much simpler than the bound-mode power method, and can be useful at least as a good first order approximation in most practical situations.

References

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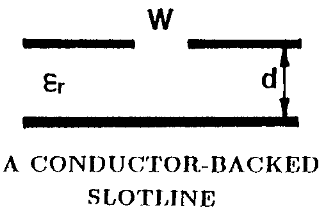

Fig.1: Geometry of a conductor-backed slotline (always leaky) that is analyzed for the characteristic impedance study.

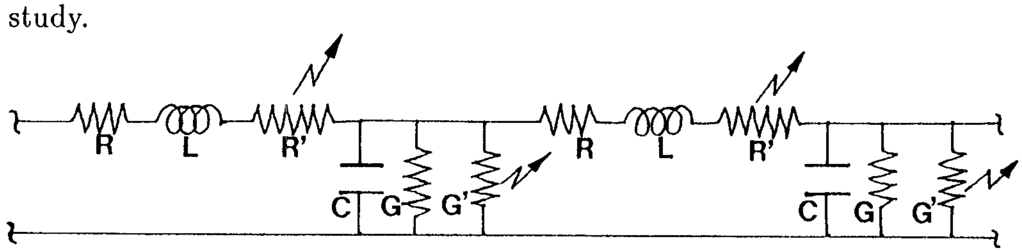

Fig.2: A generalized equivalent circuit of a transmission line with distributed radiation. R and G constitute material loss (metal and dielectric loss,) which are neglected for the present study. R' and G' are respectively the series radiation resistance and the shunt radiation conductance per unit length. R' is assumed zero for a conductor-backed slotline (the leakage is modeled as shunt type radiation.) L and C are quasi-TEM parameters.

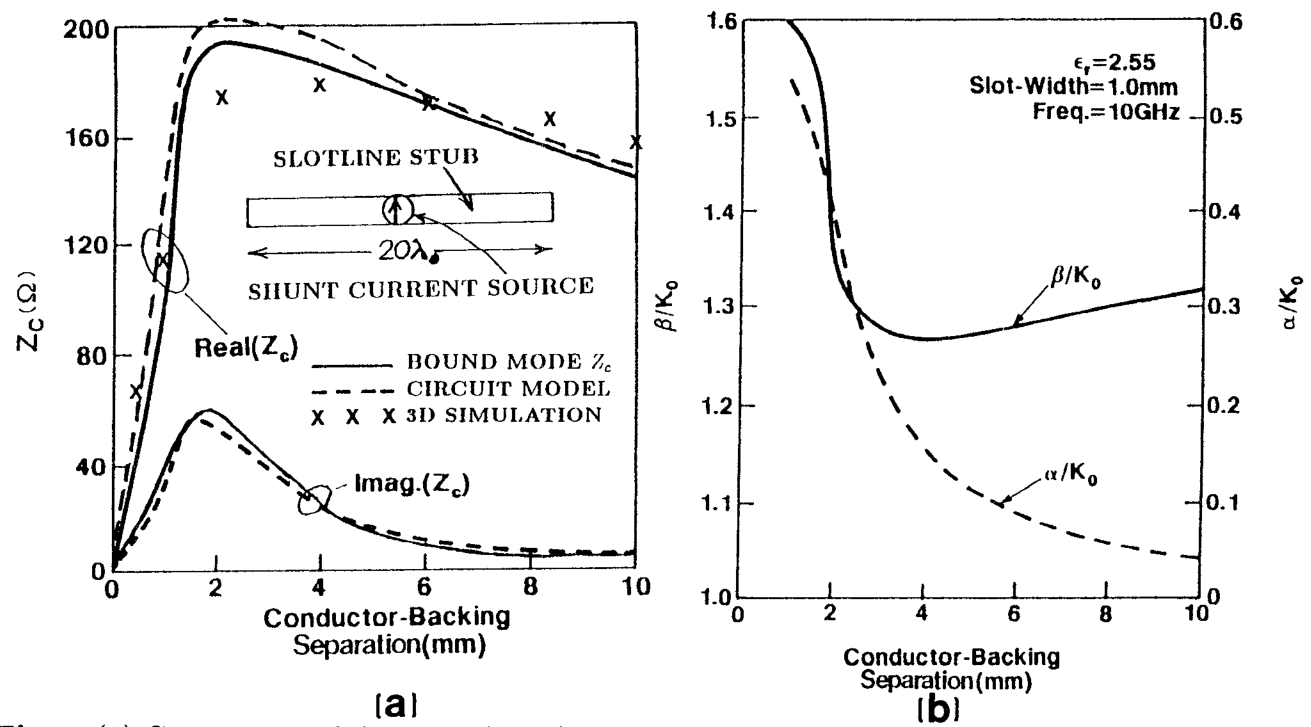

Fig.3: (a) Comparison of the equivalent characteristic impedance for different values of conductor-backing separation, d, obtained using (i) the "bound-mode Z_c" definition, (ii) the circuit model, and (iii) the 3D simulation. The 3D full-wave electromagnetic simulation was performed first to find the input impedance seen by a delta-gap shunt current source at the center of a $20\lambda_0$ long slotline (see the inset,) from which the characteristic impedance was calculated. Slot width = 1mm, $\epsilon_r = 2.55$, frequency = 10GHz. (b) The corresponding values of β and α used for the circuit model derivation.

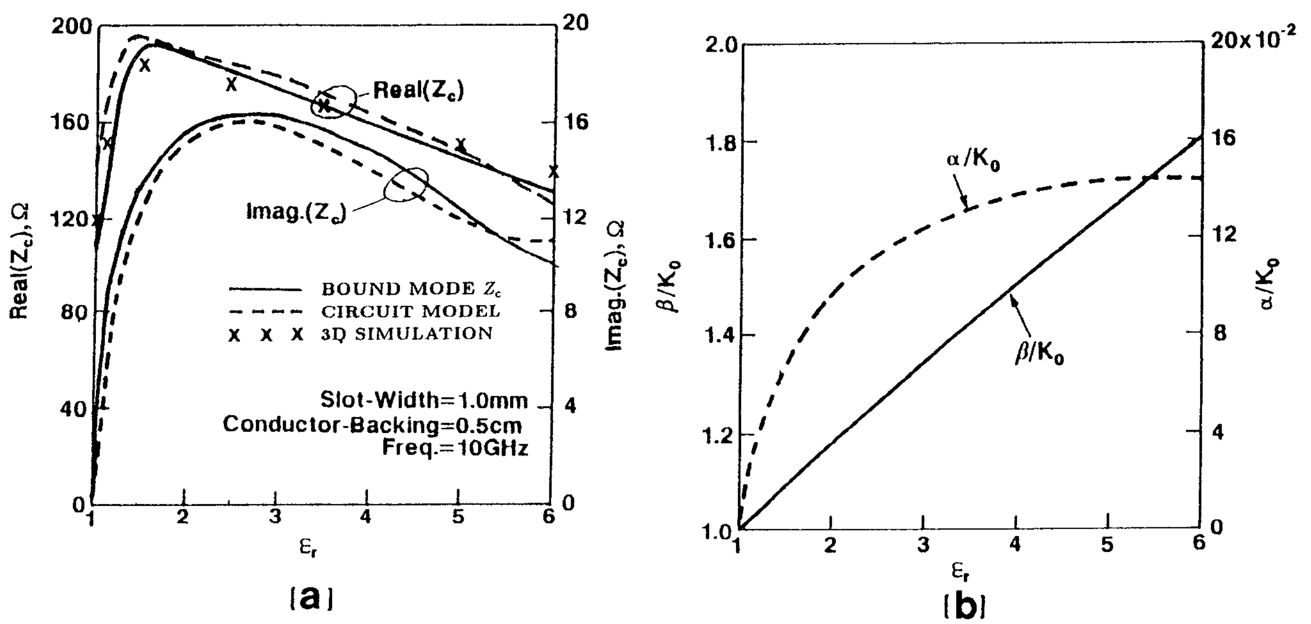

Fig.4: Results similar to Fig.3, but for different values of ϵ_r, with $d = 0.5$cm, frequency = 10GHz, slot width = 0.1cm.