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An Alternative Method for End-Effect Characterization in Shorted Slotlines

G. Duchamp, L. Casadebaig, S. Gauffre, and J. Pistre

***Abstract*—In this paper, we propose an alternative method to characterize the end effects in shorted slotlines. Using a commercial software to model the transition, a simple mathematical expression of the end impedance, valid for a given substrate family and in a wide frequency domain, was achieved. Several dielectric substrates were considered and the obtained results were compared with experimental ones. A correct agreement was observed. This approach can also be useful in more complex simulations relative to multilayer structures.**

***Index Terms*—End effect, slotline.**

I. Introduction

The development of microwave and millimeter-wave integrated circuits (MIC's) has increased and plays an important role in more recent mobile and satellite communication systems. Thus, the use of planar structures in interconnects is of greatest interest, especially microstrip lines because of their simple structure and their well-developed characterization. As a consequence, more sophisticated multilayer circuits must be considered in order to reduce the dimensions. Hence, the study of transitions between different planar transmission lines becomes necessary. For many years, several computational methods have been developed to solve electromagnetism equations in complex structures.

Two main approaches are investigated. One, generally based on semianalytical formulations, uses the method of moments and the spectral-domain approach [1]–[9], the second one considers essentially numerical algorithms like the finite-difference time-domain (FDTD) or the transmission-line matrix (TLM) method [10]–[17]. The respective benefits of these two approaches have already been discussed in the literature [3], [8], [14], [15].

In this paper, we consider the slot–microstrip transition. A rigorous study of such a structure needs to take into account the end effects which appear on these transmission lines and depend on the working frequency and linewidth. These end effects have already been characterized as capacitive or inductive according to the type of line. For microstrip lines, simple calculated models have been proposed [20]–[22]. They give a good evaluation of capacitive effects at the line termination. For the slotlines, the existing calculations are somewhat heavy and they are not so easy to use for circuit design. Furthermore, many experimental measurements have been made for different substrates and different linewidths at given frequencies in order to obtain families of charts. However, all these proposed measurement techniques [23], [24] need a large number of experimental circuits, although the results are necessarily limited because of the time needed for experiment. Using a relatively more simple method based on MDS Momentum simulation [18], we achieved and propose an efficient analytical model of end effects in a slot line, which can be simply used for many applications and more general computations.

Our results are then compared to those obtained both by experimental approaches [23], [24] and by sophisticated numerical computations [25].

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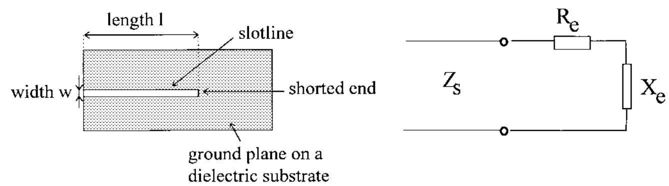

Fig. 1. Shorted slotline and its end equivalent circuit.

II. Theoretical Approach

As has been shown in the literature [25], slotline termination can be considered as a simple equivalent circuit such as a resistance and a serial inductance (see Fig. 1). Hence the expression of Z_e, the slotline end-effect impedance, is $Z_e = R_e + jX_e$ where R_e represents the radiation losses and X_e represents the inductive phenomena at the line termination.

Considering Z_s the slotline characteristic impedance, due to the non-TEM nature of the transmission mode in slot lines, Z_s cannot be defined uniquely [19], but in the present approach, we simply use the results given by the simulator. Let Z be the line impedance at a given point and $z = Z/Z_s$ be the normalized impedance at this point. z can also be written $z = (1 + \Gamma/1 - \Gamma)$, where Γ represents the corresponding reflection coefficient. With our simulator, it is possible to set a port at a given point and find Γ as S_{11}. In the case of a single-port measurement, the literal expression of the input impedance is then given by

$$z_{\text{in}} = \frac{(1 + S_{11})}{(1 - S_{11})}.$$

Let us consider a line of length l. For a given frequency, linewidth, and type of substrate, two simulation steps are necessary. The first one determines the characteristic impedance Z_s and the slot guided wavelength λ_s. In the second one, the MDS Momentum optimization module gives the S_{11} maximum value (corresponding to the maximum VSWR) in accordance to a determined length $l = \delta + (\lambda_s/2)$ where $\delta \leq (\lambda_s/2)$. Therefore, the impedance at the input port (z_{in}) is calculated and the end-effect impedance of the shorted slotline z_e is determined as

$$z_e = \frac{z_{\text{in}} - jtg\left(\dfrac{2\pi\delta}{\lambda_s}\right)}{1 - jz_{\text{in}}tg\left(\dfrac{2\pi\delta}{\lambda_s}\right)}.$$

Normalized resistances r_e and reactances x_e are plotted versus frequency for different width w and different substrates. Each curve can be simply fitted with a linear equation. Therefore, for a given substrate with a thickness h and a dielectric constant ε_r, we obtain a single expression of end reactance, which can be simply used to accurately take into account end effects in the slot for mixed microstrip–slotline structures.

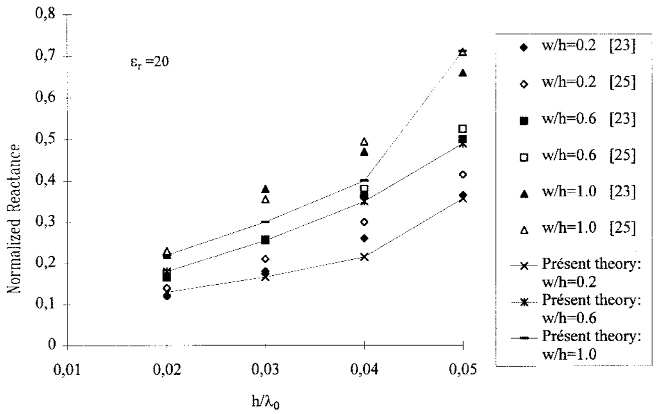

Fig. 2. Compared results of normalized short-end line reactances between present simulation and experimental curves from [23] and [25] ($\varepsilon_r = 20$).

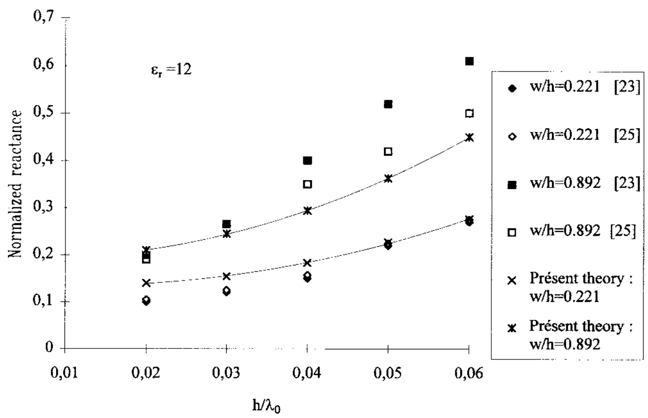

Fig. 3. Compared results of normalized short-end line reactances between present simulation and the curves from [23] and [25] ($\varepsilon_r = 12$).

III. Results and Analysis

For each width w, a simulation was made at different frequencies f_0 in the considered frequency interval of 1–20 GHz, and a set of curves for the normalized end line impedance was achieved. For two different structures with given physical and geometrical parameters ($\varepsilon_r = 20, h = 3.175$ mm and $\varepsilon_r = 12, h = 3.07$ mm), these results are then compared to those obtained experimentally by Knorr and Saens [23] and Rozzi [25]. The results are shown in Figs. 2 and 3. There is a good agreement between the present simulated approach and the experimental one for the lowest linewidth values. In the case of larger w values, a difference of about 10% appears. However, there are also dispersions of the same order between experimental values according to [23] and [25].

We then used our method to evaluate the end effects in a shorted slotline on an alumina substrate ($\varepsilon_r = 9.9$ and $h = 635\ \mu$m). In this case, the real part of Z_e (end-effect impedance), which characterizes radiation losses at the short point, was neglected and a chart of only normalized reactances x_e was plotted versus frequency for different width w (see Fig. 4). As appears in Fig. 4, the normalized reactance can be written as

$$x_e\left(f, \frac{w}{h}\right) = y\left(f, \frac{w}{h}\right) = A\left(\frac{w}{h}\right)\cdot f + B\left(\frac{w}{h}\right)$$

for $0,2 \leq (w/h) \leq 1$, f in GHz and 2 GHz $\leq f \leq 11$ GHz. $A(w/h)$ and $B(w/h)$ are fourth-degree polynomial expressions, which can be written as

$$A\left(\frac{w}{h}\right) = 10^{-3}\cdot\sum_{i=0}^{4} a_i\cdot\left(\frac{w}{h}\right)^i$$

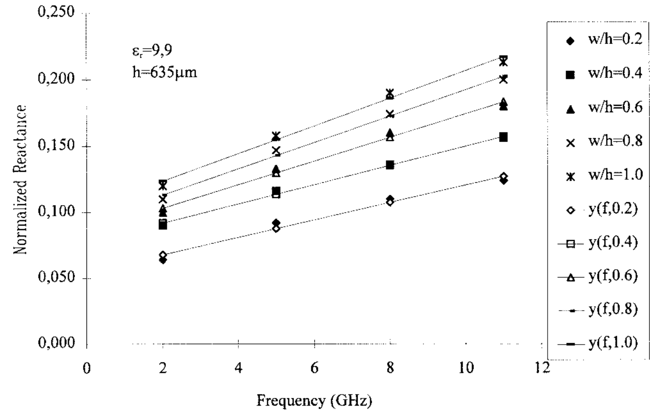

Fig. 4. Normalized reactance of short-end slotline on alumina substrate.

TABLE I
a_i and b_i Lagrange's Coefficients for Normalized End Reactance of Shorted Slotline on Alumina Substrate

i	0	1	2	3	4
a_i coefficients of $A(w/h)$	10.17	-36.03	113.364	-121.15	44.01
b_i coefficients of $B(w/h)$	-10	489.25	-1011.67	968.75	-333.34

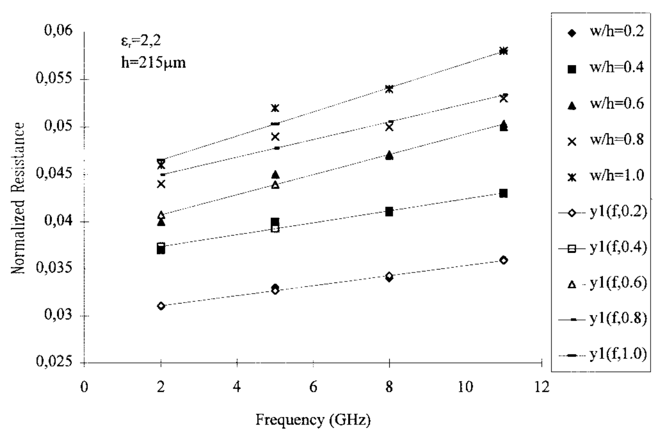

Fig. 5. Normalized resistance of shorted-end slotline on duroid substrate ($\varepsilon_r = 2,2$).

and

$$B\left(\frac{w}{h}\right) = 10^{-3}\cdot\sum_{i=0}^{4} b_i\cdot\left(\frac{w}{h}\right)^i.$$

Using Lagrange's interpolation technique, the a_i and b_i coefficients are easily determined. Table I presents these coefficients.

We have applied the same method for a duroid substrate ($\varepsilon_r = 2,2$), and the results obtained concerning the normalized resistance and reactance are presented in Figs. 5 and 6. The expressions of the normalized resistance and reactance are

$$r_e\left(f, \frac{w}{h}\right) = y_1\left(f, \frac{w}{h}\right) = A_1\left(\frac{w}{h}\right)\cdot f + B_1\left(\frac{w}{h}\right)$$

and

$$x_e\left(f, \frac{w}{h}\right) = y_2\left(f, \frac{w}{h}\right) = A_2\left(\frac{w}{h}\right)\cdot f + B_2\left(\frac{w}{h}\right).$$

As for an alumina substrate,

$$A_1\left(\frac{w}{h}\right) \quad B_1\left(\frac{w}{h}\right) \quad A_2\left(\frac{w}{h}\right).$$

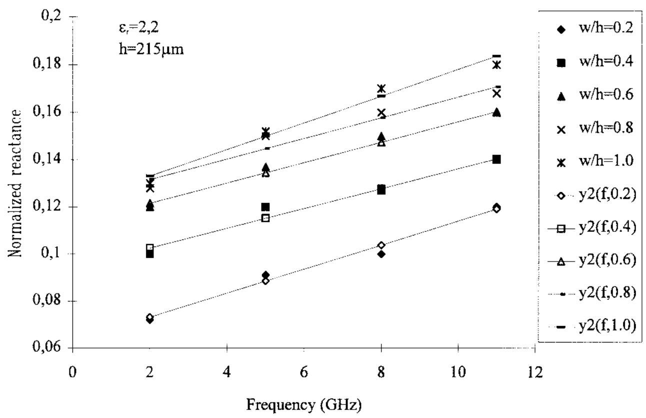

Fig. 6. Normalized reactance of shorted-end slotline on duroid substrate ($\varepsilon_r = 2,2$).

TABLE II
a_i AND b_i LAGRANGE'S COEFFICIENTS FOR NORMALIZED RESISTANCE AND REACTANCE OF SHORTED SLOTLINE ON DUROID SUBSTRATE ($\varepsilon_r = 2,2$)

i	0	1	2	3	4
a_i coefficients of $A_1(w/h)$	3.6	-30.35	97.04	-119.3	50.29
b_i coefficients of $B_1(w/h)$	4	220.42	-576.25	677.08	-281.25
a_i coefficients of $A_2(w/h)$	11.7	-58.77	164.125	-192.71	81.25
b_i coefficients of $B_2(w/h)$	10	342.42	-456.46	377.08	-151.04

$B_2(w/h)$ are fourth-degree polynomial expressions

$$A_1\left(\frac{w}{h}\right) = 10^{-3} \cdot \sum_{i=0}^{4} a_i \cdot \left(\frac{w}{h}\right)^i$$

$$B_1\left(\frac{w}{h}\right) = 10^{-3} \cdot \sum_{i=0}^{4} b_i \cdot \left(\frac{w}{h}\right)^i$$

$$A_2\left(\frac{w}{h}\right) = 10^{-3} \cdot \sum_{i=0}^{4} a_i \cdot \left(\frac{w}{h}\right)^i$$

and

$$B_2\left(\frac{w}{h}\right) = 10^{-3} \cdot \sum_{i=0}^{4} b_i \cdot \left(\frac{w}{h}\right)^i.$$

The corresponding coefficients are listed in Table II.

Therefore, for a given substrate, a unique simple expression of normalized resistance or reactance can be used to accurately take into account end effects in the shorted slotline for mixed microstrip–slotline structures.

IV. Conclusion

This paper proposes a new method for modeling of end effects in shorted slotlines. The following main results have been achieved.

1) This method allows the determination of the slot terminal impedance Z_e.
2) A comparison with experimental results, available in the literature, shows a close agreement with our own results.
3) A mathematical expression, valid for a given family of substrate and in a wide-frequency domain, has been achieved.

This could be used to determine the slot terminal impedance and, hence, permits us to take into account end line effects in microstrip–slotline transitions on this substrate family. The results corresponding to alumina and duroid substrates are presented, but equivalent relations could be easily achieved for other substrates.

This method can be generalized to characterize end effects of shorted slotlines in more general multilayer structure simulations.

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