INFLUENCE OF CONDUCTOR LOSS AND THICKNESS IN COPLANAR CIRCUIT ELEMENTS

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Abstract

The small dimensions of CPWs require due consideration of finite conductivity and metallization thickness. For this purpose an efficient Method of Lines approach for full-wave analysis of microstrip discontinuities is considerably extended. Two alternative loss models are employed depending on the skin depth. Several cascaded coplanar discontinuities including a quarterwave transformer and a double step are characterized.

1 Introduction

Coplanar waveguides (CPWs) have received increasing attention as they possess several advantages over the conventional microstrip lines for MMIC applications. However, the finite conductivity and metallization thickness strongly affect the electrical performance of a CPW circuit when the transverse dimensions are of the order of the skin depth. The propagation characteristics of various lossy CPW transmission lines have been investigated previously [1, 2]. In order to achieve high-performance, low-cost CPW components, an accurate full-wave analysis of composite structures containing discontinuities and/or 3D elements is necessary. Single discontinuities with perfectly conducting metallization of finite thickness have been analyzed [3, 4], but only few papers (e.g. [5]) have taken the conductor loss of cascaded discontinuities into account.

In recent publications various planar transmission lines have been investigated using the Method of Lines (MoL) mostly employing a 1D discretization. Losses and finite conductor thickness have been considered for longitudinally homogeneous lines [6, 7]. Another MoL approach using a 2D discretization dealt with the investigation of CPW discontinuities, assuming thin and perfect conductors [8]. This approach was restricted to simple structures consisting of few steps, because of the perpendicular orientation of the discretization lines to the substrate. Recently, an efficient algorithm has been developed for investigation of 3D microstrip discontinuities [9]. The discretization of the cross-section combined with an analytical calculation in propagation direction makes this approach very well suited for treatment of cascaded elements.

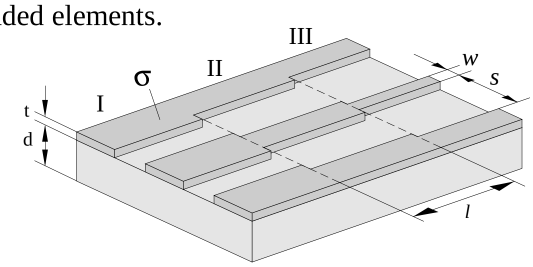

Figure 1: Cascaded CPW element

In this paper cascaded coplanar discontinuities (s. Fig. 1) are analyzed using two alternative models for finite conductivity. In the first model the conductor losses are incorporated using a self-consistent description of the conductor as a dielectric medium with large imaginary part of the permittivity [1]. Unlike the longitudinally homogeneous lines [6, 7] a 2D discretization of the cross-section is necessary for the analysis of discontinuities. This model is very well suited for the analysis of structures with metallization thickness larger or commensurate with the skin depth.

The second model is used in case of a very thin metallization (e.g. evaporated gold films of 200 nm

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thickness). The full discretization of such thin strips would increase the required memory and computation time severely and unnecessarily. Now the skin effect is irrelevant and the electrical field can be treated as homogeneous inside the metallic strips. Hence the strips are approximated by infinitely thin resistive layers with a surface conductivity calculated from the specific conductivity σ [10].

2 Theory

In the recently introduced approach for analysis of cascaded microstrip discontinuities the metallic strips are considered as perfect conductors [9]. They are excluded from the solution domain and from discretization. Their surfaces are regarded as electric walls.

In the first model based on the complex permittivity, however, not only the air and the substrate but also the whole cross-section of the conductors is discretized. Consequently, the interfaces metal-air and metal-substrate are also treated as dielectric interfaces. The field and the current distribution are calculated inside the metallic strip. This rigorous approach considers the skin-effect correctly.

In the second model we assume a very small conductor thickness. The following relation holds for the surface current density:

$$\vec{J} = t\sigma\vec{E}$$

As a consequence the electric and magnetic field components are coupled with each other. The Hertz potentials must obey novel more sophisticated boundary conditions at the conducting strips. These are in turn incorporated into the difference operators by modifying the appropriate elements. E.g. the difference operator for the first derivative of a particular potential in vertical direction is given by

$$\boldsymbol{D}_x^{\text{mod}} = \left[\begin{array}{cccc|cccc} -1 & 1 & & & & & & \\ & \ddots & \ddots & & & & & \\ & & -1 & 1 & & & & \\ & & K & -1-4K & -4K & K & & \\ \hline & & -K & 4K & 1+4K & -K & & \\ & & & & & -1 & 1 & \\ & & & & & & \ddots & \ddots \\ & & & & & & -1 & 1 \end{array}\right]$$

where K depends on σt according to

$$K = \frac{1}{C_1\sigma t + C_2}$$

In the limiting case of perfect conduction the modified difference operators tend to the unmodified ones. E.g. $\lim_{\sigma\to\infty} \boldsymbol{D}_x^{\text{mod}} = \boldsymbol{D}_x$, which employs a Dirichlet boundary condition at the upper and lower side of the strips.

The modification of the difference operators affects all the potential and some of the field equations. Moreover, the electric field components have to be calculated at additional points of the discontinuities, namely at those places where they vanish in case of perfect electric conductors. In this context the novel boundary conditions at the strips are required again. Finally, the discontinuities are cascaded by a generalized scattering matrix approach.

3 Results

A simple shielded CPW double step discontinuity is investigated as a first step. The metallization is modeled as a perfect conductor with finite thickness. In the analysis the 2D difference operators were constructed in a special way to fulfill the boundary

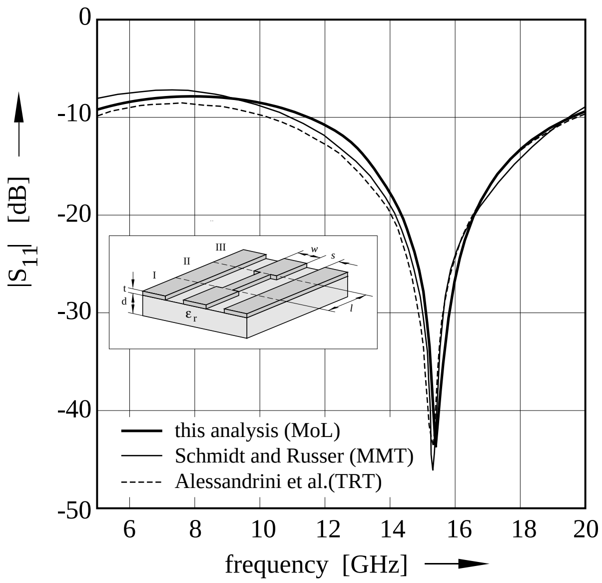

Figure 2: Reflection coefficient S_{11} of a CPW double step discontinuity with finite metallization thickness. ($w_1 = w_3 = 0.5$ mm, $s_1 = s_3 = 0.2$ mm, $w_2 = 0.2$ mm, $s_2 = 0.35$ mm, $l = 4.36$ mm, $d = 0.635$ mm, $\varepsilon_r = 9.9$, $t = 35\ \mu$m, Housing: WR28)

conditions for a metallic wall not only at the outer boundaries but also at the conductor surfaces inside the cross-section. A very good agreement of the scattering parameter S_{11} (Fig. 2) with the results of [5, 4] proves the accuracy of this modeling and the matching procedure.

Using the two alternative conductor models proposed above a great variety of lossy coplanar circuits can be analyzed. A $\lambda/4$ impedance transformer is chosen as an example for a structure with thick lossy conductors. The influence of the finite conductivity

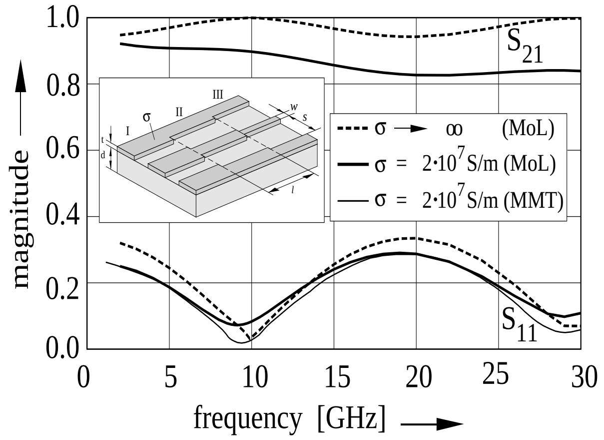

Figure 3: Magnitude of the scattering parameters of a $\lambda/4$ impedance transformer with lossy and finite conductors. ($w_1 = 20$ μm, $w_2 = 15$ μm, $w_3 = 8$ μm, $s_1 = 5$ μm, $s_2 = 10$ μm, $s_3 = 17$ μm, $l = 3.104$ mm, $d = 200$ μm, $\varepsilon_r = 12.9$, $\sigma = 2 \cdot 10^7$ S/m, $t = 3$ μm)

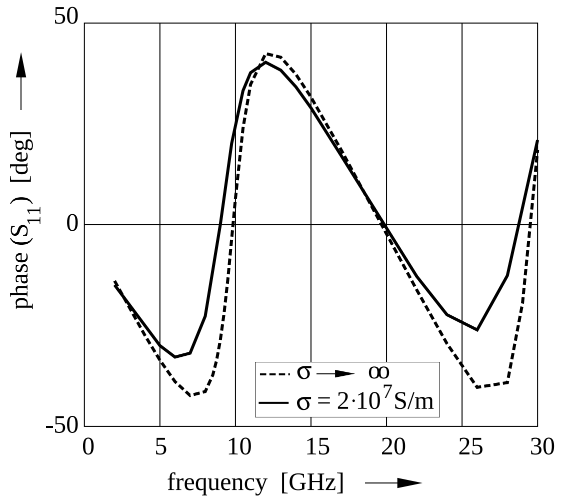

Figure 4: Phase of the reflection coefficient of the $\lambda/4$ impedance transformer described above

and thickness is clearly seen in the shift of the resonant frequency, in both the magnitude and phase of the reflection coefficient as well as in the decreasing amplitude of the transmission factor in Figs. 3 and 4.

In order to verify the model used the longitudinal component i_z of the current density is examined. Fig. 5 shows i_z inside the center conductor of a CPW corresponding to section II in Fig. 3. i_z is given at two distances y_1, y_2 from the conductor's edge and is normalized to its maximum value i_{z1} at y_1. The difference between the calculated skin depth d_e and the analytical value δ for an unbounded metallic region is less than 10 percent.

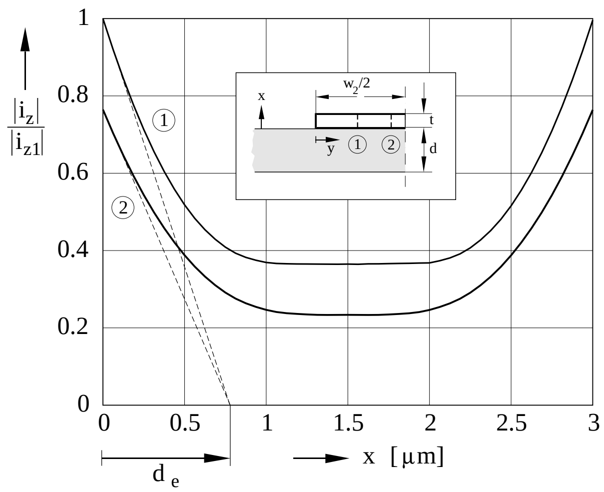

Figure 5: Longitudinal component i_z of the current density in the center conductor of a CPW at two different positions $y_1 = 2.63$ μm, $y_2 = 6.44$ μm. ($w_2 = 15$ μm, $d = 200$ μm, $\varepsilon_r = 12.9$, $\sigma = 2 \cdot 10^7$ S/m, $t = 3$ μm)

A good knowledge of the characteristic parameters of a CPW is necessary for the accurate evaluation of the scattering parameters of cascaded discontinuities. For this purpose the variation of the attenuation constant α with the conductor thickness t is studied (Fig. 6) and compared with results of a quasi-TEM approach [11]. The results obtained by both models proposed in this paper are presented. For the approximation with thin resistive layers and modified difference operators $\boldsymbol{D}_x^{\text{mod}}$ the agreement with [11] is good if the thickness is less than the skin depth $\delta = 0.593$ μm but the values deviate for $t > \delta$. The model using complex permittivity gives good results also for larger t but with higher computation time.

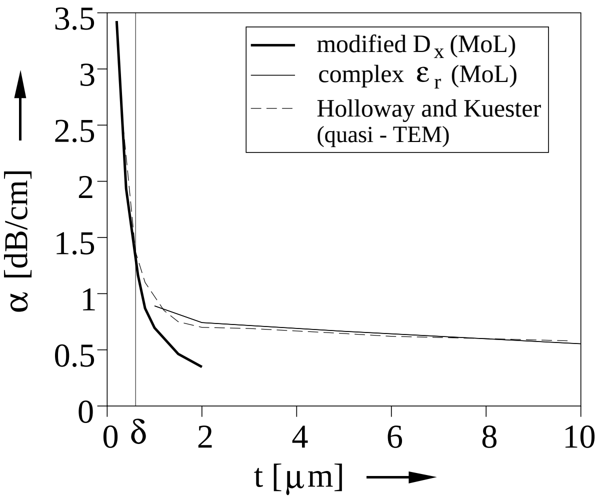

Figure 6: Variation of attenuation constant α as a function of conductor thickness t ($w/2 = 35\ \mu$m, $s = 50\ \mu$m, $\varepsilon_r = 12.9$, $\sigma = 3.602 \cdot 10^7$ S/m, $d = 200\ \mu$m, $f = 20$ GHz)

The whole range of the thickness is covered combining the two models employed here.

4 Conclusion

Using the proposed method various composite CPW structures including 3D elements can be analyzed accurately. The finite conductor thickness as well as the ohmic losses, which can severely influence the performance of the circuit, are taken into account. It is possible to choose between two different ways of treating the finite conductivity depending on the ratio of the conductor thickness to the skin depth. Hence an efficient analysis is guaranteed for discontinuities in a great variety of CPWs.

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