# FULL-WAVE SIMULATION OF TRANSMISSION LINE STRUCTURES IN MICROWAVE MONOLITHIC INTEGRATED CIRCUITS

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## ABSTRACT

Future Si-based analog and digital highly integrated Microwave Monolithic Integrated Circuits (MMIC) are expected to operate at frequencies up into the millimeter-wave range. Further reduction of circuit dimensions will require multilayered wiring and transmission line structures with cross-sectional dimensions of the conductors in the order of micrometers. In order to achieve further reduction in conductor losses copper is also considered for internal wiring. The exact modelling of the transmission properties of the line structures requires full-wave modelling of the electromagnetic field in the semiconductor and insulator regions as well as within the conductors. In this paper various transmission line structures have been analyzed using the Mode Matching (MM) approach. Based on the numerical simulation transmission an equivalent network-oriented circuits are extracted.

## INTRODUCTION

The application of copper as conductor material and the use of damascene technology is a promising way for future realization of highly integrated MMICs for frequencies of operation up to several 10 GHz. Compared to aluminium copper exhibits significantly lower electro-migration and better electrical and thermal conductivity [1, 2]. The higher possible current density in copper transmission lines allows a decrease in the cross-section of the conductors. Damascene technology allows one to reduce the size of transmission lines to 2.5 µm width and 0.4 µm height. The dimensions of the conductors are comparable with the skin depth, therefore an accurate simulation and optimization of the structures of the transmission lines requires full-wave modelling of the electromagnetic field inside the conductors as well.

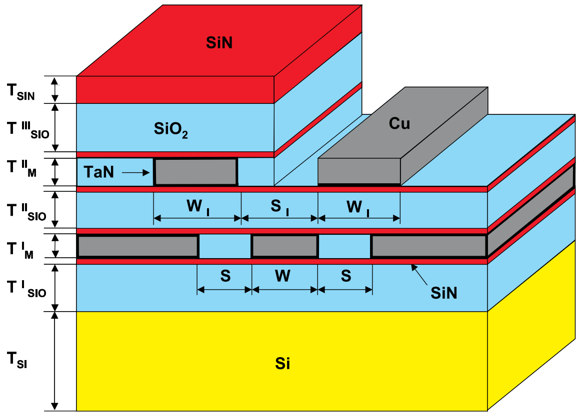


Figure 1: Schematic view of the simulated multilayered geometry.

## TECHNOLOGY

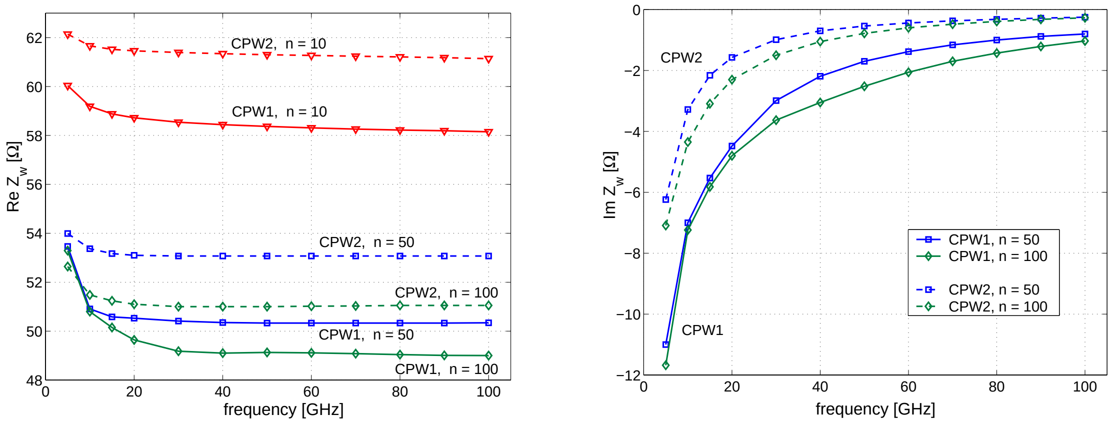
In damascene technology trenches for the transmission lines and vias are first etched into the substrate ($SiO_2$). A very thin insulating layer of TiN or TaN is then deposited as a barrier between the substrate and copper to avoid diffusion of the copper into the $SiO_2$ layer. A thin copper film is evaporated and all trenches and holes for vias are filled at once in a galvanic process (dual damascene process). The surplus copper on the surface of the wafer is removed afterwards by chemical-mechanical polishing, then the surface is covered by etching stopper ($Si_3N_4$). After this a further $SiO_2$ layer can be placed on top and these steps may be repeated up to 6 times. The result is a multilayered structure with various transmission line structures, i.e. coplanar waveguide (CPW), stripline, microstrip line, conductor backed CPW (see Fig. 1).

## THE MODE MATCHING APPROACH

In transmission lines with strip width and height in the skin depth's order of magnitude conductor loss influences the propagation characteristics severely. One of the most efficient methods for numerical simulation of such homogeneous two-dimensional structures is the mode matching method [4, 3]. The field inside the conductors, playing an important role, is completely taken into consideration. In the MM method the structure is subdivided into homogeneous subdomains. At the boundaries of the subdomains the tangential field components of the partial waves are matched. The method of moments is used to determinate the amplitudes of the partial waves. Truncating the complete set of eigenmodes numerical results depend on the set of testing functions used in the method of moments.

## SIMULATIONS RESULTS

Various types of transmission lines are considered. From various investigations it turned out that the coplanar waveguides are advantageous compared to other line types in respect of the attenuation caused mainly by the conductor loss. For example, microstrip lines always show higher attenuation due to the thickness of the $\mathrm{SiO}_2$ layer which is fixed by technological reasons. Two $50\,\Omega$ CPWs of different dimensions are simulated. The simulations are performed with following material parameters: $\varepsilon_{\mathrm{Si}} = 11.9$, $\sigma_{\mathrm{Si}} = 5.5 \cdot 10^{-4}\,\mathrm{S/m}$, $\varepsilon_{\mathrm{SiO_2}} = 3.9$, $\tan\delta_{\mathrm{SiO_2}} = 10^{-4}$, $\sigma_{\mathrm{Cu}} = 5.9 \cdot 10^{7}\,\mathrm{S/m}$, vertical dimensions: $T_{\mathrm{Si}} = 380\,\mu\mathrm{m}$, $T^{I}_{\mathrm{SiO_2}} = 4.9\,\mu\mathrm{m}$, $T^{I}_{M} = 0.6\,\mu\mathrm{m}$, $T^{II}_{\mathrm{SiO_2}} = 4.15\,\mu\mathrm{m}$, $T_{\mathrm{SiN}} = 0.55\,\mu\mathrm{m}$. The first CPW (CPW1) has the dimensions: $W = 7.5\,\mu\mathrm{m}$, $S = 2.5\,\mu\mathrm{m}$; the size of the second CPW (CPW2) is twice as large: $W = 15\,\mu\mathrm{m}$, $S = 5\,\mu\mathrm{m}$. In Fig. 2 the numerical results for the characteristic impedance of two CPWs are shown in dependance of the number $n$ of partial waves considered in the simulation. Due to the losses, the imaginary part of the wave impedance (see Fig. 2(b)) cannot be neglected. In Fig. 3(a) the attenuation coefficient in $\mathrm{dB/mm}$ of different CPW geometries is compared. The attenuation coefficient increases severely with frequency, especially for CPW1. The substrate attenuation is lower than $0.005\,\mathrm{dB/mm}$. In order to obtain accurate numerical solutions at higher frequencies the number of partial waves should be significantly increased. The effective permittivity is presented in Fig. 3(b) for the same structures. The electromagnetic field concentrates more in the $\mathrm{SiO}_2$ substrate with increasing frequencies. On the basis of numerical results useful network-oriented models can be obtained through equivalent circuit representation. The characteristic impedance of a transmission line may be represented by



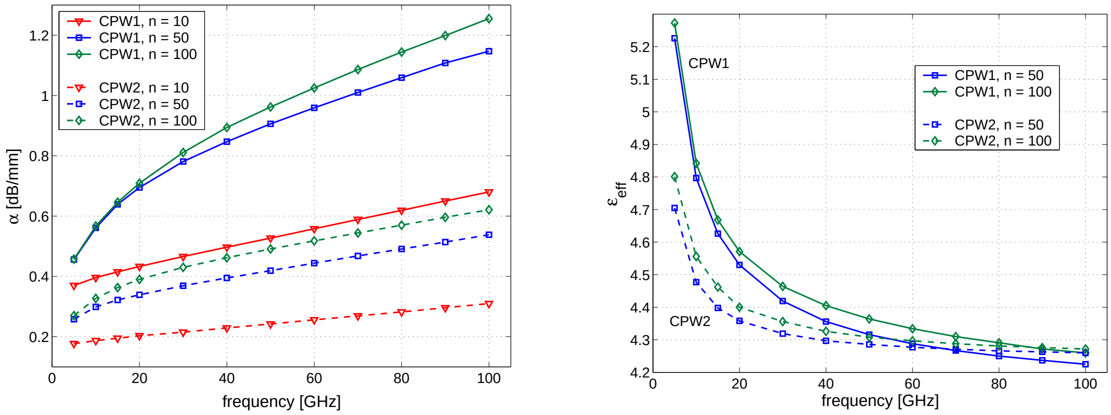
(a) Real part of the characteristic impedance

(b) Imaginary part of the characteristic impedance

Figure 2: Characteristic impedance of different CPWs.

$$Z_w = \sqrt{\frac{Z'(\omega)}{Y'(\omega)}} = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}}. \tag{1}$$

The loss in the conductor is described by the series resistance per unit length $R'$ which is at the same time frequency dependent due to the skin effect and increases proportionally with the square root of the frequency. The inductance per unit length $L'$ represents a component dependent on the geometry and the skin effect. The conductance per unit length $G'$ portrays the loss associated with the transverse electric field in $\mathrm{Si/SiO_2}$ substrates while $C'$ represents the capacitance per unit length. The impedance $Z'(\omega)$ describing the skin effect in conductor can be modelled with arbitrary accuracy by



(a) Attenuation

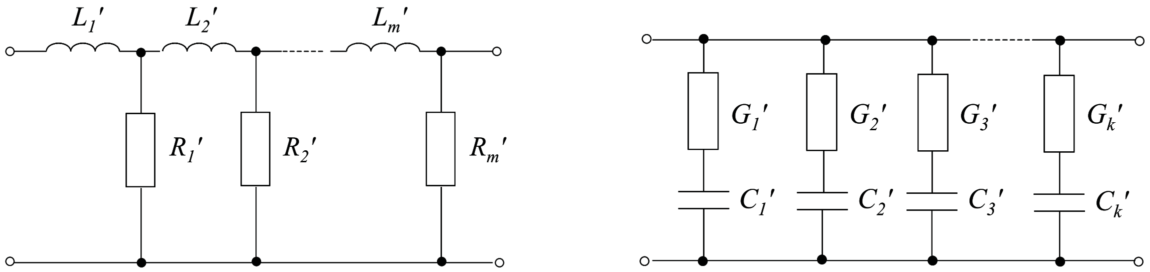
(b) Effective permittivity

Figure 3: Attenuation and effective permittivity of different CPWs.

ladder network [5] according to Fig. 4(a). The complex impedance $Z'(\omega)$ with a finite number of *LR*-sections is given recursively by

$$Z'(\omega) = \left\{ \begin{array}{l} \mathrm{j}\omega L'_1 + \cfrac{1}{\cfrac{1}{R'_1} + \cfrac{1}{\mathrm{j}\omega L'_2 + \cfrac{1}{\cfrac{1}{R'_2} + }}} \\ \qquad\qquad\qquad\qquad \ddots \\ \qquad\qquad\qquad\qquad\qquad + \cfrac{1}{\cfrac{1}{R'_{m-1}} + \cfrac{1}{\mathrm{j}\omega L'_m + R'_m}} \end{array} \right\} . \tag{2}$$

The *LR*-ladder networks represents a wide-band model of the skin effect. The accuracy of the model increases with the number $m$ of *LR*-sections. Fig. 5(a) and Fig. 5(b) compares the frequency dependencies of the real and the imaginary part of $Z'(\omega)$ at $m = 10$. The admittance $Y'(\omega)$ is modelled by a *CG*-ladder network as depicted in Fig. 4(b). Fig. 6(a) and Fig. 6(b) show the approximation of $Y'(\omega)$ at $k = 3$.



(a) *LR*-ladder network circuit

(b) *CG*-ladder network circuit

Figure 4: Network circuits.

## CONCLUSION

In this contribution the full-wave analysis and comparative study of different transmission lines using the MM technique are presented. High-frequency and millimeter-wave MMICs in damascene technology are made up of transmission line structures with cross section in the micrometer range. This requires full-wave modelling of the electromagnetic waves propagating on the lines. Based on the results an equivalent circuit for the transmission line is extracted, which can be used in different network-oriented circuit simulators.

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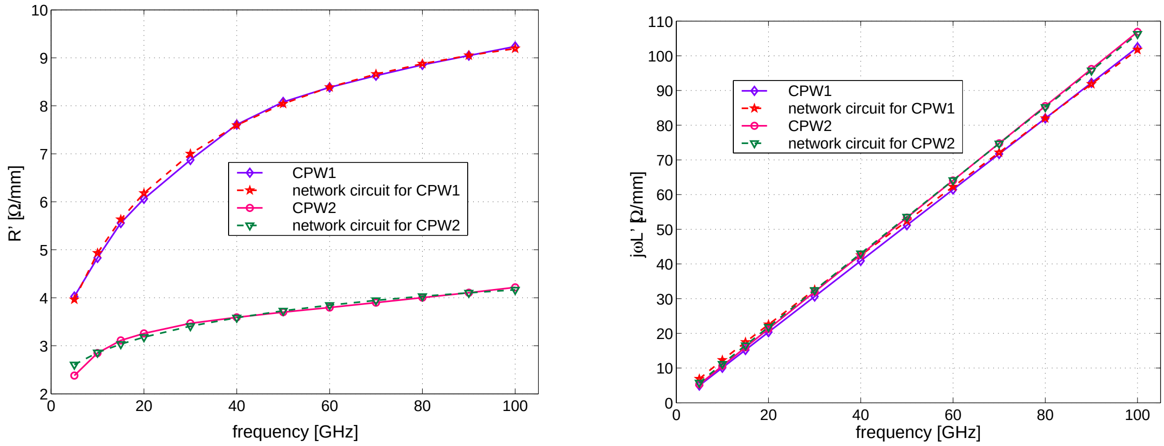
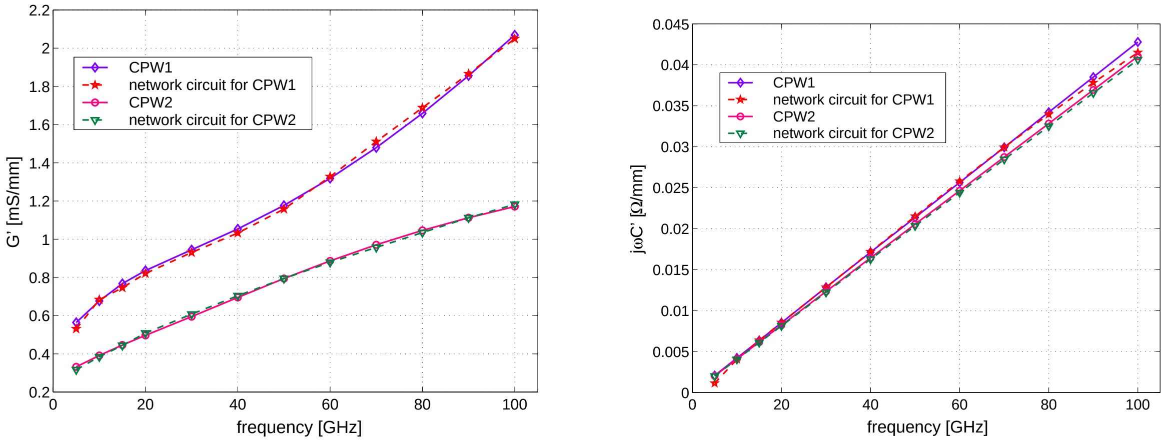


(a) $R'$

(b) $\mathrm{j}\omega L'$

Figure 5: Real and imaginary part of $Z'(\omega)$ impedance.



(a) $G'$

(b) $\mathrm{j}\omega C'$

Figure 6: Real and imaginary part of $Y'(\omega)$ impedance.

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