Rigorous Analysis of the Characteristic Impedance in Conductor-Backed Miniature Coplanar Waveguides Considering Multiple Layers of Lossy and Finite Thickness Metal

Ke Wu and Ruediger Vahldieck

Laboratory for Lightwave Electronics, Microwaves and Communications
(LLiMiC)
Department of Electrical and Computer Engineering
University of Victoria
Victoria, B.C., V8W 3P6, Canada

ABSTRACT

This paper present a complete investigation of realistic conductor-backed miniature coplanar waveguides based on GaAs and allumina substrates. A self-consistent approach is used together with the method of lines to determine characteristic impedances, losses and propagation constants. This analysis is general and includes not only the finite thickness and conductivity of metallization but also the effect of first and second metallic layers and the via-hole location. Results are compared with those obtained with the mode-matching method and published measured data.

Introduction

Conductor-backed coplanar waveguides (CBCPW) are realistic uniplanar transmission lines in monolithic microwave integrated circuits (MMIC) and miniature hybrid MIC (MHMIC). Due to the miniaturized dimensions, the conductor thickness is in the order of the skin depth [1] and the conductor losses are not negligible. To characterize CBCPW accurately, in particular at higher frequencies (>30GHz), hybrid-mode analysis becomes necessary, to include first and second layer metallization losses, dielectric losses, via hole location and back-metallization losses.

In previous papers, full-wave methods like the mode-matching method and the method of lines (MoL) [2,3,4,6] have been used in conjunction with a self-consistent description of the lossy metallization. However, up to now mainly the propagation constant (dispersion) and loss properties have been studied. The characteristic impedance was never investigated in great detail and no data is available for CPW's with first and second layer metal, where each layer has a different conductivity. Although some aspects of the characteristic impedance for finite thickness conductors in CPW have been presented in [4], only the voltage-current definition was used. This definition, however, does not accommodate the case where higher order modes start to propagate, because the voltage is not any more concentrated in the slot and the current may be distributed along the groundplane rather than being concentrated around the center conductor. The power/voltage or power/current definition may provide a more realistic picture about the behaviour of the characteristic impedance, in particular when the operating frequency is close to the cutoff frequency of a higher order mode. This is so, because the power is calculated over the entire cross-section of the transmission line and, therefore, includes also the field in areas which are left out in the voltage-current definition.

In this paper we present a detailed analysis of the characteristic impedance using the MoL together with a self-consistent description of the metal layers. The procedure used in this analysis can be summarized as follows:

A. Since the conductors are treated as ordinary lossy dielectric layers, a multilayered dielectric waveguide with inhomogeneous subregions is modeled. The imperfect backmetallization can be regarded as an additional layer with thickness of the skin depth or any specific dimension and with finite conductivity.

B. After discretizing the electric and magnetic potential functions in x-direction, the Helmholtz and Sturm-Liouville equations can be decoupled into a set of ordinary differential equations whose solutions correspond to simple wave equations in y-direction.

C. Applying the field continuity equation at the dielectric interface and cascading the resulting matrices lead to a space-domain characteristic matrix which must be transformed back into the original domain. The complex propagation constant is obtained by finding the zeros of the determinant of the characteristic matrix equation.

D. From the characeristic matrix equation the field quantities and the transmitted power can be calculated in the original discrete domain.

E. The characteristic impedance can be obtained by the power-voltage and power-current definition where the voltage and current are defined in the slot and around the center conductor, respectively, while the power is calculated over the entire cross-section of the transmission line.

Results

Fig.1 shows the propagation constant, loss and characteristic impedance of a GaAs CBCPW and a comparison with results obtained by the mode matching method [4]. A good agreement between both approaches is observed except that a slightly higher loss for line (a) is obtained by our approach. Note that the impedance based on the voltage-current definition, obtained by the mode matching method, coincides well with our results (power-voltage definition). The complex characteristic impedance based on the power-current definition is generally higher than that from the power-voltage definition.

Another interesting comparison between our results and measurements [5] is shown in Fig.2. Up to 20GHz there seems to be a good agreement between measured results and our computed data (Fig.2a). At higher frequencies, however, the measured results reported in [5] for the characteristic impedance, propagation constant and losses show some erratic behaviour, which can be explained by the occurence of higher order modes. At about 20GHz the first higher order mode starts to propagate. This mode has a magnetic field symmetry and can therefore interfere with the fundamental mode. As Fig.2b further shows, this higher-order mode is mainly influenced by the position of the via-holes. Moving the via-hole position from d = 0.6 mm to

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1.1 mm, changes significantly the cutoff frequency of this mode up to 30GHz. At the same time the losses for this mode decrease rapidly. This observation correlates with the measured results of the losses in [5]. This indicates that the losses measured in [5], from that frequency on, are more likely losses of this higher order mode. This interpretation is also supported by the computed results for the characteristic impedance (Fig.2c), which decreases when a higher-order mode starts to propagate. The measured Zo does not decrease but starts to behave erratic up to about 35 GHz and then shows smooth behaviour about 50Ω. If we look at the computed characteristic impedance for the higher-order mode, we realize a strong increase in its value up to 50Ω. This value remains constant from 35GHz on. Overlapping Fig.2c with Fig 2d suggest that the measured impedance at frequencies higher than 35GHz is rather that of the higher-order mode than that of the fundamental mode. Although this discussion is speculative, it seems to be certain, based on our theoretical investigation, that the erratic behaviour of the propagation characteristics measured in [5] is due to higher-order mode propagation. As Fig.2 illustrates, these higher-order modes can be suppressed up to a degree by moving the via holes closer to the slots [7].

Fig.3 illustrates the effect of a composite metallic layer on the transmission properties and complex characteristic impedance. A full-wave analysis of composite metal microstrip was reported in [8] without investigating the characteristic impedance. In this paper we include the characteristic impedance and extend the investigation to CPW. Two cases are compared: Fig.3a shows the case where an additional metallic layer is added only to the center conductor, while Fig.3b shows the case where the center conductor consist of only one layer and the groundplane (left and right from the center conductor) is composed of two metallic layers. It is found that by adding a metallic strip (4 μm in this example) only at the top of the central conductor, the overall transmission losses can be improved by 0.01 to 0.02 dB/mm depending on the frequency range. At the same time, the absolute value of the complex characteristic impedance and propagation constant drops.

Fig.4 presents design aspects of the CBCPW versus slot width and width of the central conductor for both GaAs and alumina substrates. As illustrated, the impedance is more sensitive to the miniature circuit dimensions. It is found that the impedance continues to decrease with increasing w (s = 50 μm), while it remains constant for values of s>100μm (w = 50 μm).

Conclusion

A detailed investigation with respect to the characteristic impedance in CBCPW has been presented in this paper. It was shown that the onset of higher-order modes limits the useable frequency range in CBCPW and that the via hole location is crucial to extend this frequency range. It was also shown that the characteristic impedance shows some dependency on the first and second layer metal used for the conductor and groundplane.

References

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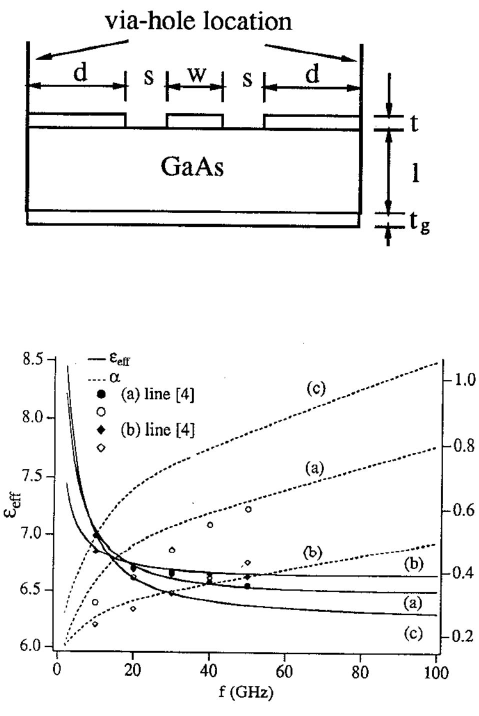

Fig.1

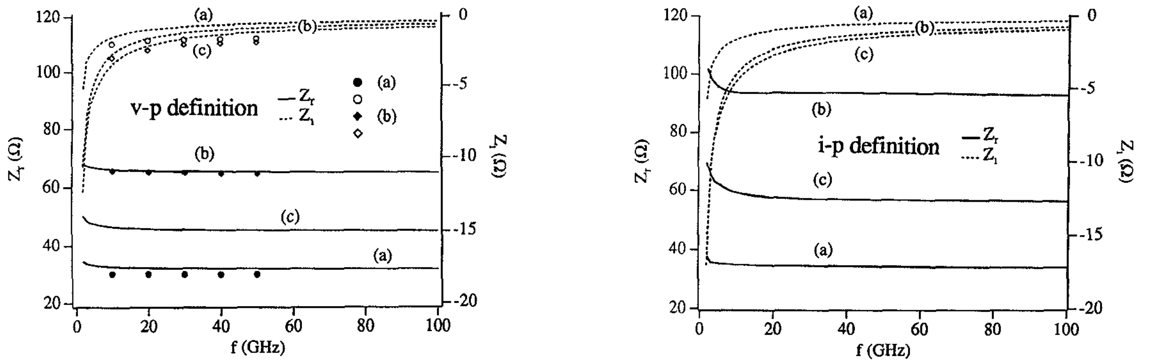

Fig.1: General comparison of numerical results obtained by this approach with those of the mode-matching method. (t = 1.5 μm, d = 50 μm, l = 600 μm, t_g = 5 μm, σ = 3 × 10^4 $(\Omega mm)^{-1}$)
(a) line: w = 40 μm, s = 5 μm. (b) line: w = 10 μm, s = 20 μm.(c) line: w = 10 mm, s = 5 μm.

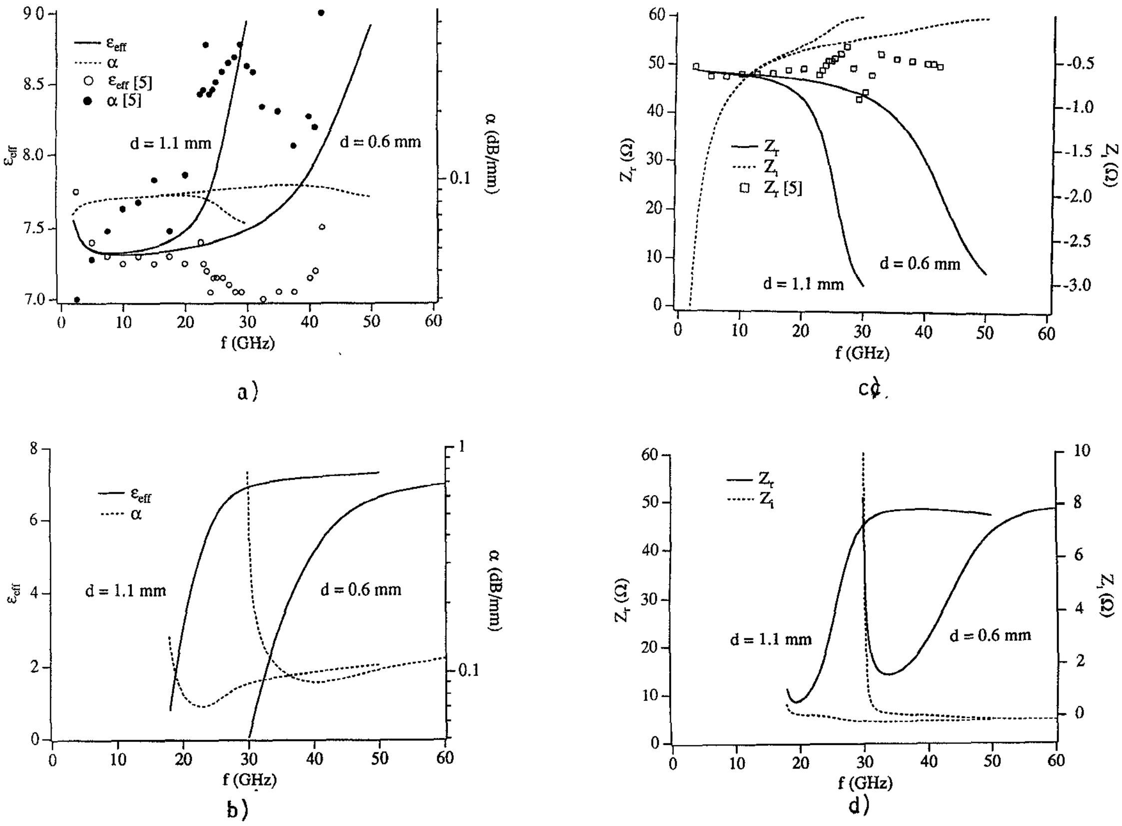

Fig.2: Fundamental and higher order mode (magnetically symetric) characteristics in terms of propagation constant, loss and complex characteristic impedance of a conductor-backed coplanar waveguide (CBCPW) based on 100 μm GaAs substrate. (t = 1.5 μm, l = 100 μm, t_g = δ (skin depth), w = 51 μm, s = 50 μm, σ = 3 × 10^4 $(\Omega mm)^{-1}$).

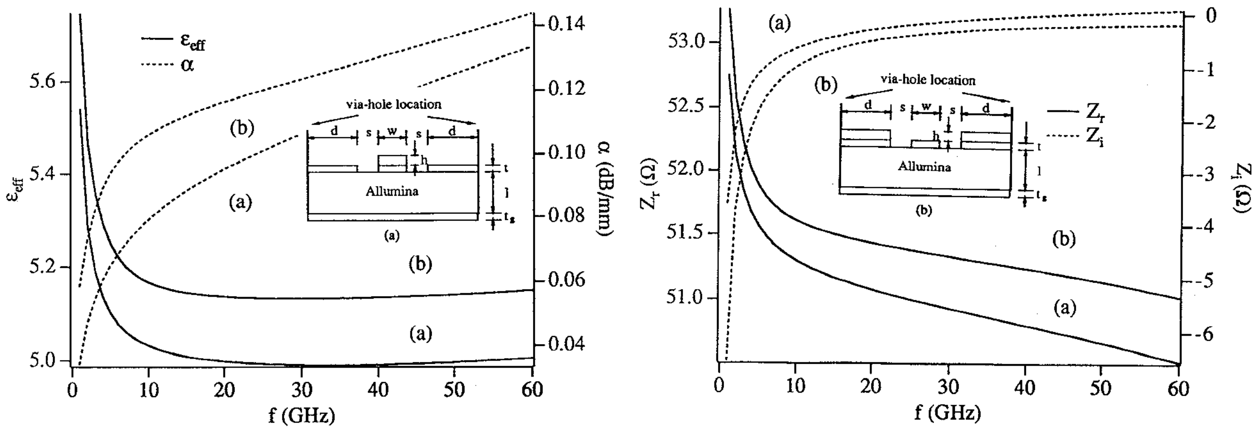

Fig.3: Influence of two different metal-composite allumina-based CBCPWs on transmission properties and complex characteristic impedance. (l = 254 μm, s = 25 μm, w = 50 μm, d = 100 μm, t = 1.0 μm, h = 4 μm, top metallic layer $\sigma = 3.1 \times 10^4$ $(\Omega mm)^{-1}$ and bottom metallic layer $\sigma = 3.7 \times 10^4$ $(\Omega mm)^{-1}$).

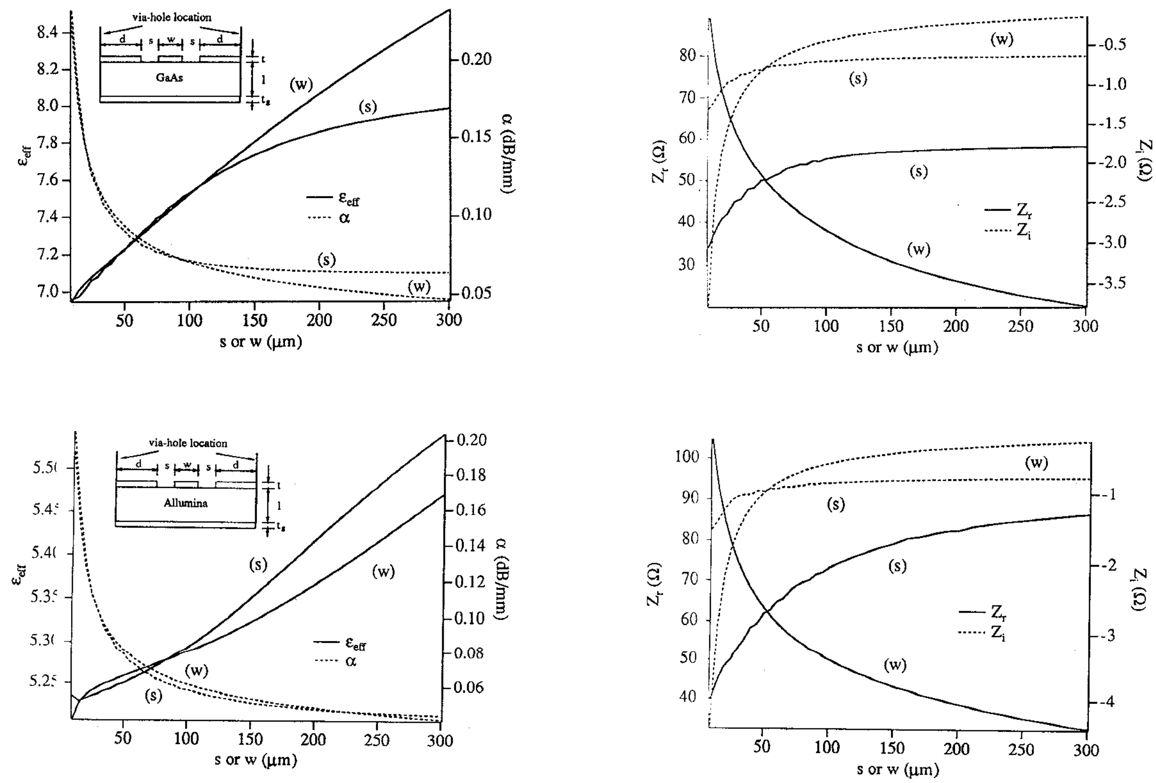

Fig.4: Complex characteristic impedance and transmission properties as functions of slot-width and width of central conductor for both 254 μm allumina and 100 μm GaAs CBCPWs. (t = 1.5 μm, d = 100 μm, s = 50 μm for (w) line, w = 50 μm for (s) line, $\sigma = 3 \times 10^4$ $(\Omega mm)^{-1}$).