Comparison of coplanar waveguide models at millimetre wave frequencies

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***Abstract*—This paper investigates an improved empirical model predicting the propagation characteristics of coplanar waveguides (CPW) at G band based on a conventional analytical CPW model. A comparison with another quasi-analytic CPW model and fullwave em simulations is presented. The comparison results demonstrate that the improved CPW model shows excellent agreement with measurements on different substrate materials up to 220 GHz. This means that, for the first time, a comprehensive and efficient CPW description at higher frequency ranges up to G band is available. This improved CPW model can be applied and used during the design cycle of hybrid integrated circuits (ICs), monolithic microwave integrated circuits (MMICs) and printed circuits board (PCBs). Moreover, the enhanced accuracy of the improved CPW model can help to reduce uncertainties in on-wafer CPW-based measurements.**

***Index Terms*—coplanar waveguides, leakage, radiation, surface waves**

I. Introduction

Planar transmission lines are widely used in many applications ranging from wireless communications and 5G Multiple-Input Multiple-Output (MIMO) systems to automotive radar and medical sensing. In fact they form the core of any integrated circuit (IC), monolithic microwave integrated circuit (MMIC) or printed circuits board (PCB). To this end, their main feature is that they are compatible with the planar scheme of those integrated circuit concepts. Moreover, they can be easily scaled and are suitable for batch processing [1]. Since RF circuit design relies on an accurate description of the passive components, it is important to precisely model and characterize the RF characteristics of planar transmission lines.

A number of different planar transmission lines is being used in hybrid ICs, MMICs and PCBs. The most common ones are the coplanar waveguides (CPW) and microstrip (MS) lines. A short overview of the advantages and disadvantages of different types of planar transmission lines is given in [1]. One disadvantage of MS structures for example is the requirement to use additional via holes when contacting the ground. This causes parasitic inductances deteriorating the RF performance [2]. Moreover, while such via holes are available in many MMIC processes, they may require additional technological steps in other cases. CPW on the other hand with all the metals residing in the same plane represents a good alternative to the MS approach. In recent years, several models, e.g. [3] and [4] have been developed and proposed to model the CPW characteristics as accurately as possible. The approach of [3] is based on a transmission line formalism resulting from a spectral representation of the integral equations. The benefits of this approach are multifold, e.g. it predicts the propagation of CPW on infinite substrates or substrates with backside metalization. However, one limitation of the model of [3] is the assumption of an infinite ground width w_g. It has been found in several works [5], [6] and [7] that the influence of the CPW ground width is one of the main causes for radiation losses and dispersion effects and it is responsible for a distinct dip behavior observed in many measurement results [4], [5] and [7].

On the other hand, the CPW model of [4], as a modified version of [8], already incorporates the influence of the finite CPW ground width. A closed-form empirical formula has been implemented to describe the radiation effects of the higher-order mode more precisely. However, this formula so far has only been validated for CPWs up to W band.

When transmission lines in state-of-the-art MMIC technologies are used, the models of [3] and [4] both allow precise modeling of CPWs up to subterahertz frequencies. This paper addresses this frequency range and benchmarks the two models. The goal is to investigate their respective validity and to find out which model is more precise and can serve as a reference for future comparisons.

This paper presents the comparison between the model of [4] and the quasi-analytic model of [3]. To validate the models, the calculated results are verified by measurements and fullwave 3D em simulation performed with [9] up to G-band frequencies.

II. Comparing the different CPW models

Using three different cases this section presents a thorough comparison between the three CPW models, the model of [8] (referred to as conventional CPW model), the quasi-analytic approach of [3] (referred to as quasi-analytic CPW model), and the improved CPW model of [4] (referred to as new improved CPW model). Both attenuation constant α and effective permittivity $\epsilon_{\text{r,eff}} = (\beta/\beta_0)^2$ representing radiation and dispersion effects are first studied considering the 3 models only, without validation by em simulation results or measurements.

TABLE I
CPW DIMENSIONS

Case	w/s/w_g/t (µm)	ϵ_r	κ (MS/m)	tanδ
1	62/6/250/0.534	3.78	20.5	$8 \cdot 10^{-4}$
2	50/25/270/6.5	9.7	36	$1.25 \cdot 10^{-4}$
3	25/15/100/1	12.9	25	$1 \cdot 10^{-4}$

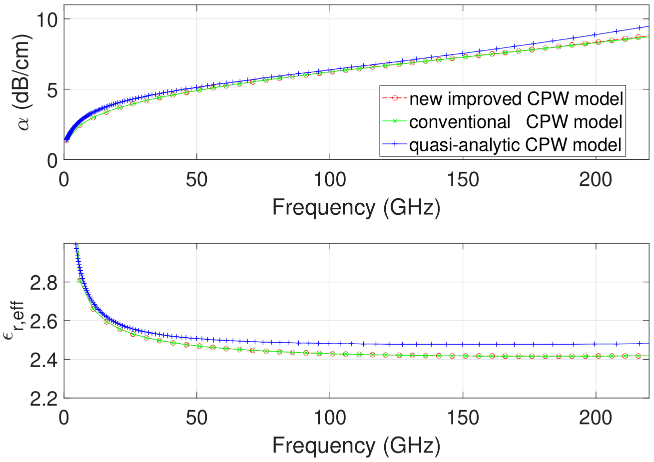

Fig. 1. Attenuation constant α in dB/cm and effective permittivity $\epsilon_{\mathrm{r,eff}}$ for Case 1.

A. Different substrate materials

The substrate materials selected for the investigation are fused silica (ϵ_r = 3.78), alumina (ϵ_r = 9.7) and GaAs (ϵ_r = 12.9), all of which are materials commonly used for on-wafer calibration purposes ([6], [10] and [11]). The CPW geometries of the three substrate materials are dimensioned to obtain approximately 50 Ω. Table I provides the data for the three substrates, which are referred to as Case 1, Case 2 and Case 3 in the following. The common CPW parameters are the CPW signal width of w, the gap of s, the ground width of w_g and the metal thickness of t whereas the material parameters are the electrical conductivity of κ (MS/m) and the dissipation factor of tanδ.

Fig. 1 shows the calculated attenuation constant α and effective permittivity $\epsilon_{\mathrm{r,eff}}$ for Case 1 (fused silica with a relatively low ϵ_r). The conventional and the new improved CPW model deliver similar results. The attenuation constant of the quasi-analytic CPW model though, assuming an infinite CPW ground width, is comparable to the conventional and new CPW model up to 150 GHz. Beyond this frequency, a slight increase of the attenuation curve can be detected. For the effective permittivity, the situation is different. Here, the conventional and the new CPW model reveal similar results and the quasi-analytic CPW model shows overall a slight shift. The deviations at f = 220 GHz are around $\Delta\epsilon_{\mathrm{r,eff}}$ = 0.0626 with 2.6 % (using the new improved CPW model as reference). This can be explained from the assumption of infinite CPW ground width in [3]. In case of an infinite CPW ground width the electric fields are more concentrated inside the substrate thus increasing the capitance per unit length C' and in turn the effective permittivity.

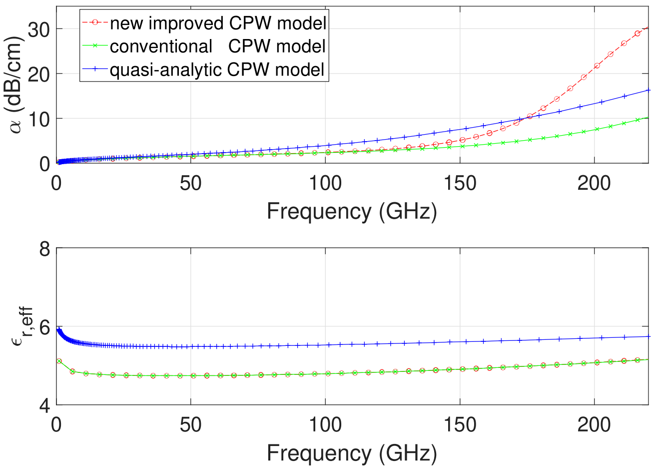

Fig. 2. Attenuation constant α in dB/cm and effective permittivity $\epsilon_{\mathrm{r,eff}}$ for Case 2.

This behavior becomes more evident when materials with larger permittivity such as in Case 2 and Case 3 are used. Fig. 2 shows the calculated propagation constants for Case 2 where alumina is used. Here, the overall difference between the effective permittivity has risen to $\Delta\epsilon_{\mathrm{r,eff}}$ = 0.5824 (11.3 %). In the attenuation constant, significant differences (qualititatively as well as quantitatively) are found. The conventional and the new CPW model both show a similar curve behavior only up to f = 140 GHz. Beyond 140 GHz the new CPW model shows a steady increase which is then flattened at f = 220 GHz. The quasi-analytic CPW model exhibits completely divergent results. The results of Case 3 also confirm the above observation (see Fig. 3). Here, the results of the conventional and new CPW model are almost identical in both propagation constants. The propagation constants of the quasi-analytic CPW model differ significantly.

Summarizing the results, one can state the following.

- Case 1: CPW on fused silica substrate – In general, all three models yield similar results with only slight differences for the attenuation. For the effective permittivity, the conventional and the new CPW model also deliver identical results, whereas the effective permittivity of the quasi-analytic CPW model shows deviations around 2.6% at f = 220 GHz.
- Case 2: CPW on alumina substrate – All three CPW models show divergent results for the attenuation constant due to radiation effects. For the effective permittivity, the conventional and the new CPW model deliver identical results, whereas the results of the quasi-analytic CPW model diverge with pronounced deviations of 11.3 % at f = 220 GHz.
- Case 3: CPW with narrow ground width on GaAs substrate - Similar observations like in Case 1 and Case 2 can be made, but, because of the small ground width, the

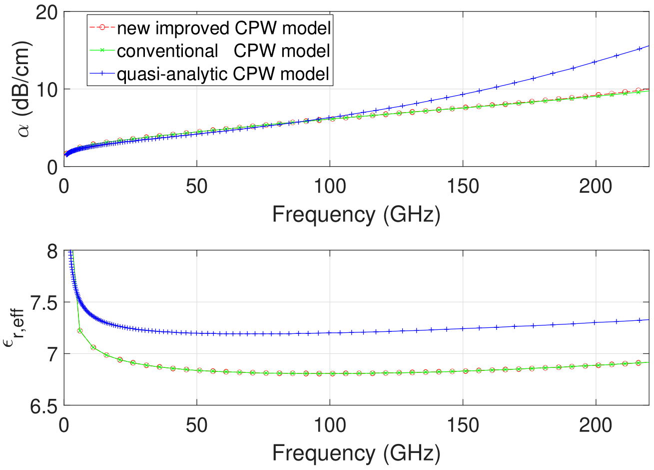

Fig. 3. Attenuation constant α in dB/cm and effective permittivity $\epsilon_{\text{r,eff}}$ for Case 3.

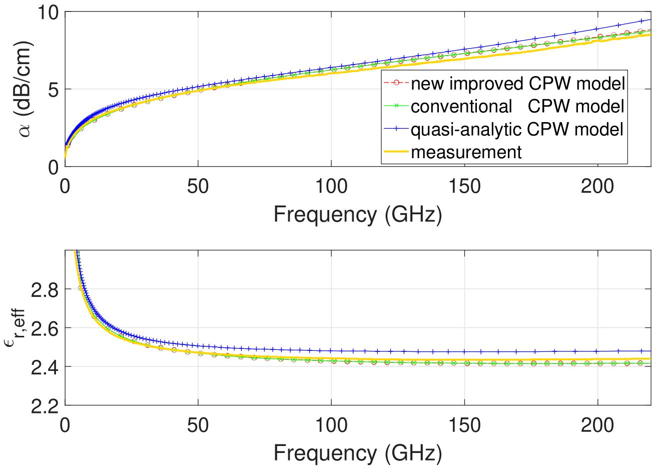

Fig. 4. Attenuation constant α in dB/cm and effective permittivity $\epsilon_{\text{r,eff}}$ for Case 1 compared with measurement.

extensions of [4] do not contribute visible differences.

These results indicate that the influence of finite CPW ground has to be considered. The quasi-analytic CPW model with an infinite CPW ground is only applicable in Case 1 where a fused silica substrate is used. When other materials with higher dielectrics are used, all three CPW models reveal divergent results. The differences become especially pronounced at higher frequencies when the transversal dimensions are no longer small compared to the wavelength. Among the three cases, Case 2 represents the case where all the three CPW models show the largest deviations.

III. Measurement Results

Finally, the results have been verified against measured data. Due to the narrow ground width (w_g = 100 µm) of Case 3 the measurement results are found to be affected by parasitic probe effects [12]. Additionally, due to the dense layout design the measurement results are shadowed by crosstalk effects between adjacent structures and probe coupling effects with neighboring structures [13]. Therefore, only calibration substrates with the dimensions of Case 1 and Case 2 are used for comparison and verification. Full calibration sets consisting of a short as reflect standard, a 400 µm long CPW line as thru and seven additional lines with lengths of 500, 700, 900, 2400, 5400, 7400 and 11400 µm were designed, manufactured and characterized. Measurements of the two calibration sets (Case 1 and Case 2) were performed for different frequency bands. All the measurements were carried out on a ceramic chuck using GGB probes with different probe pitches in the different frequency bands. Overall, a wide frequency range up to 220 GHz was considered. The measured data was then processed with the multiline Thru-Reflect-Line (mTRL) [14] algorithm which yields the propagation constants.

The measurement results for Case 1 are shown in Fig. 4. As can be seen the conventional and new improved CPW model show excellent agreement with the measurement results. The results of the quasi-analytic CPW model are close to the measured data, though deviating a bit more. Therefore, it is more interesting to have a look at Case 2.

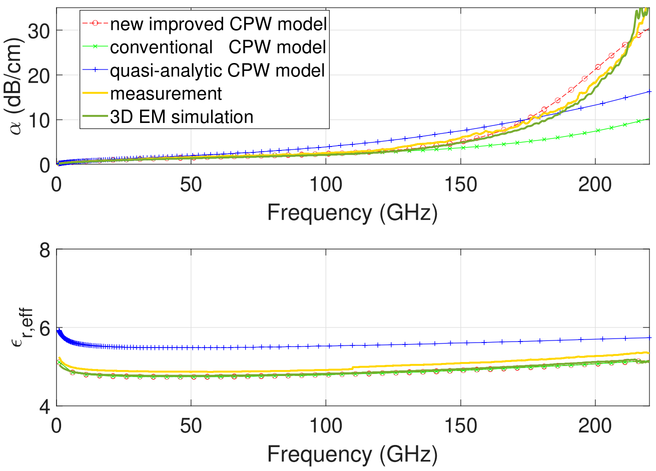

Fig. 5. Attenuation constant α in dB/cm and effective permittivity $\epsilon_{\text{r,eff}}$ for Case 2 compared with measurement.

The corresponding measurements are plotted in Fig. 5. The small discontinuities between the different frequency bands which are especially visible at 110 GHz (see $\epsilon_{\text{r,eff}}$ in Fig. 5) are caused by the different measurement instrumentation and different probe pitch sizes used in the respective frequency bands. Here, a clear conclusion can be drawn. Both, the measured attenuation constant and the attenuation constant from 3D fullwave em simulations [9] show excellent agreement with the new improved CPW model. The deviations between the measurement and the other two CPW models are significant. Among all the models investigated, the new improved CPW model represents the best approximation with decent agreement to the measurements and simulations.

IV. Conclusion

This paper investigated a newly introduced approach [4] for accurately modeling the propagation characteristics of CPWs, which refined an existing CPW model incorporating high-frequency effects, namely radiation (caused by higher-order mode excitation) and dispersion effects. A comparison with another quasi-analytic tool and fullwave em simulations proved the validity of the model of [4]. The results were further validated by measurements on different substrate materials up to f = 220 GHz. Thus, it has been shown for the first time that the propagation characteristics of CPWs can be predicted with excellent precision up to G band. The improved modeling accuracy forms the basis for successful MMIC design and also helps to better predict on-wafer measurement uncertainties.

Acknowledgment

The authors acknowledge support by the European Metrology Programme for Innovation and Research (EMPIR) Projects 14IND02 PlanarCal and 18SIB09 TEMMT. Both projects (14IND02 and 18SIB09) have received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

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