Paper

Analysis of errors in on-wafer measurements due to multimode propagation in CB-CPW

Arkadiusz Lewandowski and Wojciech Wiatr

Abstract—We study for the first time errors in on-wafer scattering parameter measurements caused by the parasitic microstrip-like mode propagation in conductor-backed coplanar waveguide (CB-CPW). We determine upper bound for these errors for typical CPW devices such as a matched load, an open circuit, and a transmission line section. To this end, we develop an electromagnetic-simulations-based multimode three-port model for the transition between an air-coplanar probe and the CB-CPW. Subsequently, we apply this model to examine errors in the device *S* parameters de-embedded from measurements affected by the parasitic MSL mode. Our analysis demonstrates that the multimode propagation in CB-CPW may significantly deteriorate the *S*-parameters measured on wafer.

Keywords— *on-wafer measurements, multimode propagation, error analysis, conductor-backed coplanar waveguide (CB-CPW), microstrip-like mode, numerical electromagnetic analysis, on-wafer probe, calibration, de-embedding, monolithic microwave integrated circuit (MMIC).*

1. Introduction

The advent of a new wafer-level measurement technology, the on-wafer microwave probing [1], has resulted in proliferation of the coplanar waveguide (CPW) as a basic transmission medium for connecting dies with standard measurement instrumentation through microwave coplanar probes. Although this technology greatly alleviates on-wafer measurements of monolithic microwave integrated circuits (MMICs), it also brings about fresh metrology problems. Some of the problems result from the fact that in typical measurement configurations the CPW becomes an overmoded transmission line. This is due to the fact that, besides the three strips placed on the upper substrate side, the CPW comprises usually a backside metallization plane, which is either plated on the substrate or introduced by the chuck of the on-wafer measurement station [1]. Such a four conductor CPW structure is called a conductor-backed coplanar waveguide (CB-CPW) and in general supports three modes [1, 2]: a coplanar mode (CPW), a slot-line mode (SLM) and a microstrip-like mode (MSL), which is also referred to as a parallel-plate mode [3]. Since both CB-CPW structures and microwave coplanar probes contacting them usually maintain symmetry, the slot-line mode is virtually not excited and therefore is not considered in this work. Of the two remaining modes, CPW is the desired one that usually dominates over the parasitic MSL mode.

There are two basic approaches to the moding in the CB-CPW: the conventional one neglecting undesired modes and using an approximate single-mode representation, and the complete one taking into account all modes. The former utilizes the well-known circuit theory methods [4], stemming from the assumption of the single mode propagation, while the later refers to a more general multimode waveguide circuit theory [5], at an expense, however, of a higher complexity. With a constant increase of the maximum frequency of MMICs, the accuracy of the conventional approach becomes insufficient for a fast and effective design of high-speed electronic circuits which is essential for shortening time-to-market and reducing costs. Therefore, one needs novel circuit analysis and measurement characterisation methods that take into account the multimode propagation effects in MMIC structures.

A general theoretical basis for multimode waveguide circuit theory methods has already been laid in [4, 5]. Furthermore, numerical electromagnetic (EM) 3D simulation techniques, that have rapidly advanced in the last few years, have been successfully applied in the analysis of the propagation and excitation properties of the MSL mode, as well as means of its suppression [2, 3, 6–9].

However, as regards the on-wafer metrology, there have been only a few works dealing with the influence of the parasitic MSL mode on the measurement accuracy of CB-CPW based structures. Potential errors in the on-wafer multiline-TRL calibration [10] on the CB-CPW are mentioned in [11]. A trial to quantify these errors in case of the TRL calibration [12] is presented in the previous conference paper of the authors [13].

The aim of this work is to fill up this gap by presenting a systematic analysis of errors occurring in the measurements of CB-CPW based structures due to the presence of the parasitic MSL mode. The topic is a continuation of [13]. Here, we study first multimode excitation in a transition between an air-coplanar probe and a CB-CPW line using 3D EM simulations, and then model this transition with a multimode three-port scattering matrix. In the next step, we use this model to examine some exemplary one- and two-port CB-CPW structures and determine errors in the conventional single-mode approach arising due to the presence of the parasitic MSL mode. Results show that these errors may be significant.

2. Multimode excitation in an air-coplanar-probe-to-CB-CPW transition

In general, a microwave coplanar probe has a very complicated design, optimized in terms of low insertion and return loss, as well as low radiation [1]. Accurate modelling of all probe's characteristics is thus a very tedious and time consuming task. However, considering excitation of the parasitic MSL mode, the most important part of the probe is the discontinuity arising at the contact between the probe-tip and the CPW transmission line.

A simplified analysis of this excitation may be performed using approaches that rely on the mode matching technique applied to the quasi-static description of both modes in terms of modal voltages and currents [2, 3]. Although these methods are particularly useful for understanding the MSL mode excitation phenomena, their feasibility is limited to simple discontinuities and low frequencies, for which dispersion effects are negligible [6]. Therefore an exact analysis of the MSL mode excitation calls for numerical EM simulations.

Taking this into account, we construct a model of the probe depicting fairly well the probe-tip and investigate multimode excitation at the probe-tip discontinuity using numerical EM simulations. A view of the probe model placed over a section of the CB-CPW is shown in Fig. 1. The picture presents only a half of the whole symmetric structure which has been split with a magnetic wall along the center of the signal strip in order to reduce the analysis time.

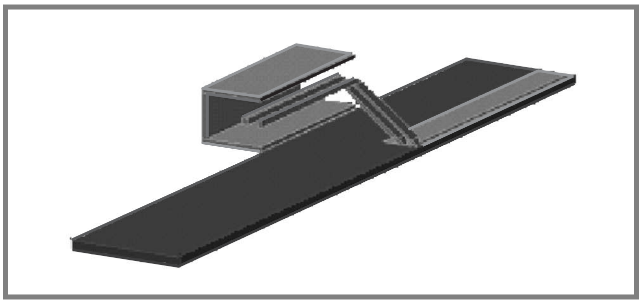

Fig. 1. A half-view of the air-coplanar-probe-to-CB-CPW transition.

The probe consists of two parts: a simplified launching section and a precisely modelled contacting part. The launching section comprises an air CPW surrounded by a rectangular waveguide, while the contacting section consists of an air-coplanar line declining at an angle to the substrate and ending with a contacting tip. The probe tip has dimensions of a real microwave probe: pitch of 150 μm, center conductor width of 50 μm, and contact length of 50 μm.

In our analysis, we consider typical lines on an alumina substrate used mainly for manufacturing of impedance standard substrates (ISS), and lines on a typical MMIC GaAs substrate. Their dimensions, given in Table 1, were chosen to provide 50 Ω characteristic impedance for the CPW mode.

Table 1
Parameters of lines used in the EM simulation: w – centre strip width, s – slot width, w_g – ground strip width, h – substrate height, and ε_r – relative dielectric permittivity

Line	h [μm]	ε_r	w [μm]	s [μm]	w_g [μm]
ISS	635	9.9	50	25	250
GaAs	100	12.95	50	48	250

We performed the EM simulations with the QuickWave software package, employing the method of finite-differences in time-domain (FDTD) [14]. At first we determined field distributions and dispersion characteristics of the CPW and MSL modes for both substrates in the frequency range from 5 to 15 GHz. Figure 2 shows the effective dielectric permittivity of both modes. In each case, the effective permittivity of the CPW mode does not depend

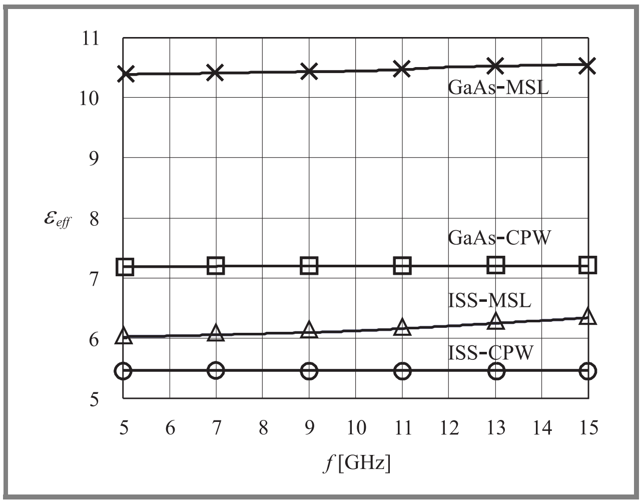

Fig. 2. Effective permittivity for the CPW and MSL mode in ISS, and the CPW and MSL mode in GaAs.

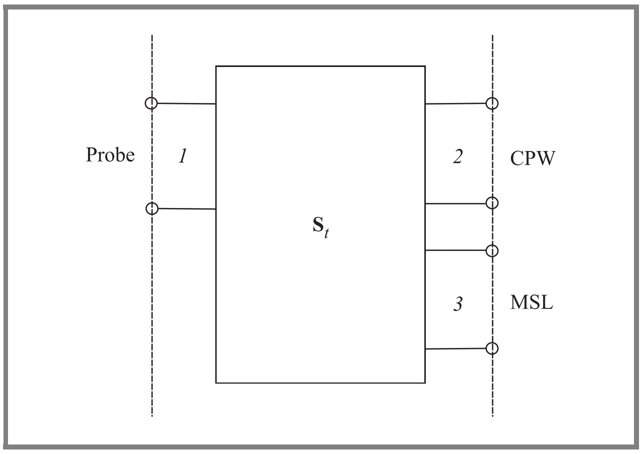

Fig. 3. Three-port model of the transition represented with a scattering matrix $\mathbf{S}_t$.

on frequency, while the effective permittivity of the MSL mode is higher and its slope reveals a small dispersion.

Next, we analysed electrical properties of the transition determining its multimode scattering matrix $\mathbf{S}_t$. Figure 3 shows the three-port model of the transition, in which port *1* is associated with the probe's launching part, while ports *2* and *3* correspond to the CPW and MSL modes, respectively. In the simulation their reference planes were placed at the end of the CB-CPW line to prevent coupling through higher order modes. After the simulation the reference planes have been shifted down to the probe tip to account for the electrical properties of the transition itself.

Figure 4 shows magnitude of the scattering parameters S_{21} and S_{31}, representing transmission for the CPW and MSL mode, respectively. The graphs demonstrate a significant signal transmission on the MSL mode for both substrates, which is slightly higher for the GaAs substrate because of thinner substrate in comparison to the total line width [2].

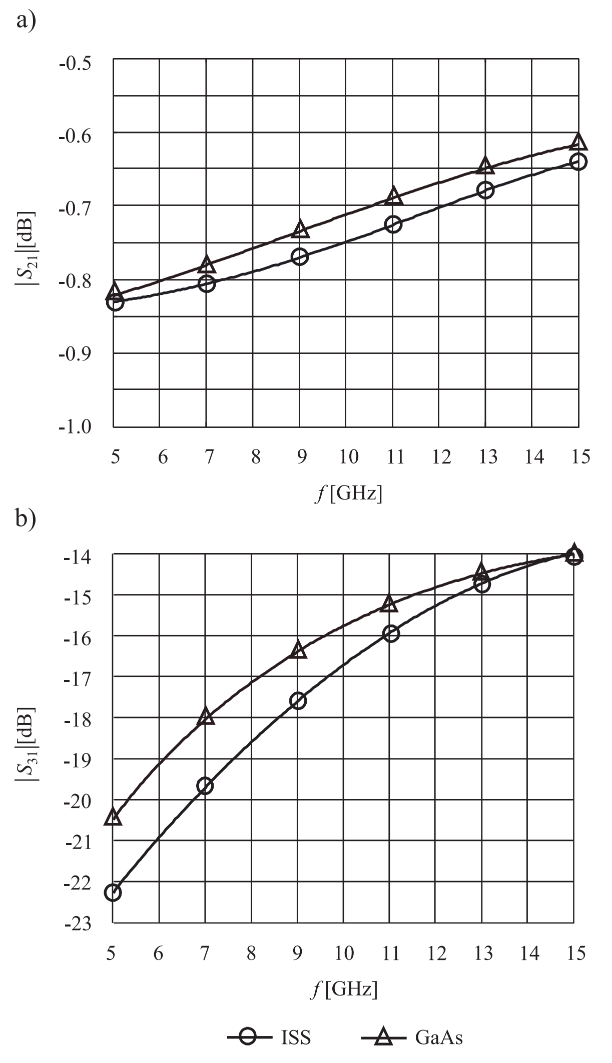

Fig. 4. Scattering parameters (a) S_{21} and (b) S_{31} of the transition between an air-coplanar probe and the CB-CPW on the ISS and GaAs substrate.

3. Errors in measurements of typical devices

When measuring CB-CPW devices, one is usually interested in device parameters for the CPW mode. Consequently, the conventional device measurement is based on neglecting the MSL mode and employing a single-mode device description. In this approach, the device under test (DUT) is modelled as a linear two-port embedded into a cascade of two other linear two-ports representing systematic measurement errors [1]. Thus, the conventional *S*-parameter measurement procedure relies on removing the errors from the DUT measurements and is performed in two steps: probe calibration[1] and device de-embedding [1].

The probe calibration is based on measuring several known devices to determine the systematic errors introduced by the probes. For this purpose, diverse calibration methods are applied, among which SOLT, LRRM [15], and various versions of TRL [10, 12] are the most frequently used [1]. After the calibration, the parameters of both embedding two-ports, each representing the relevant probe, are known and their effect on the measurement can be easily removed in the de-embedding procedure basing on the conventional single-mode waveguide circuit theory [4].

However, this straightforward conventional approach may introduce some errors when the single-mode assumption is not met. In the reality, the CPW mode is accompanied by the parasitic MSL mode and they both simultaneously contribute to the measured signal [5]. If the effect of the MSL signal is not negligible, multimode errors emerge in the DUT *S*-parameters.

To assess these errors, we mimic the conventional approach employing, however, the multimode matrix $\mathbf{S}'_t$ of the probe-to-line transition. We perform our study in two steps, first analysing the calibration procedure, and then the device de-embedding.

Since in the conventional approach probes are represented by two-ports, application of the single-mode calibration procedure to the multimode case leads to a reduction of three-port matrix $\mathbf{S}_t$ to a two-port matrix $\mathbf{S}'_t$. Such a reduction can be carried out uniquely when all measured CPW devices exhibit the same reflection coefficient for the MSL mode. However, if it is not the case, this reduction is ambiguous, and matrix $\mathbf{S}'_t$ strongly depends on the type of standards employed in the calibration [13]. Therefore, to avoid such problems in the calibration, we assume to deal with an ideal case, i.e., when the MSL mode is suppressed and all energy is transmitted over the CPW mode. Such a situation approximately takes place for thick substrates and may be arranged in practice by inserting an additional thick dielectric layer between the CPW substrate without backside metallisation and the chuck [2]. The characteristic impedance for the MSL mode becomes then very high in comparison to the CPW mode, which is equivalent

[1]For the sake of simplicity we assume here that the vector network analyzer (VNA) has been calibrated at the coaxial reference planes.

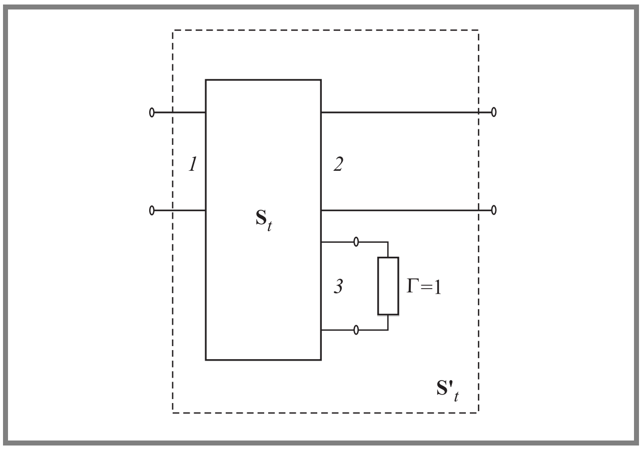

Fig. 5. Reduction of the three-port to a two-port model.

to attaching an open circuit at the MSL mode port of the three-port as shown in Fig. 5. Consequently, the determination of the matrix $\mathbf{S}'_t$, representing the systematic measurement errors of the probe, becomes straightforward.

Having calculated the matrix $\mathbf{S}'_t$, we are able to simulate the de-embedding of multimode measurements for one-port and two-port devices whose parameters for CPW are assumed to be known. To study the errors, we simulate the measurement results using the three-port model with some general assumptions regarding properties of the MSL circuit. The errors are defined as a deviation of the de-embedded *S*-parameters in reference to the parameters assumed for the CPW mode. Two next subsections present results of the error analysis for a matched load and an ideal open circuit, as exemplary one-port devices, and a CB-CPW transmission line section with a varying length, as a two-port device.

3.1. Matched load and ideal open circuit

We analyse multimode propagation errors in measurements of a matched load and an ideal open circuit by investigating the influence of different loading conditions for the MSL mode. The basic idea of our approach is depicted in Fig. 6.

For a CPW device with a reflection coefficient Γ_{CPW} we measure a reflection coefficient Γ_m, which is different from Γ_{CPW} because of the systematic errors brought in by the probe and the contribution of the MSL mode, represented by the variable reflection coefficient Γ_{MSL}. From Γ_m we de-embed the reflection coefficient Γ'_{CPW} using the single-mode description $\mathbf{S}'_t$ of the probe and employing the relationship:

$$\Gamma'_{CPW} = \frac{\Gamma_m - S'_{t11}}{S'_{t22}\Gamma_m - \det \mathbf{S}'_t}. \quad (1)$$

We seek for bounds of Γ'_{CPW} deviations from the true value, Γ_{CPW}, considering dependence of Γ'_{CPW} on Γ_{MSL} under the condition of passiveness of the later $|\Gamma_{MSL}| \leq 1$.

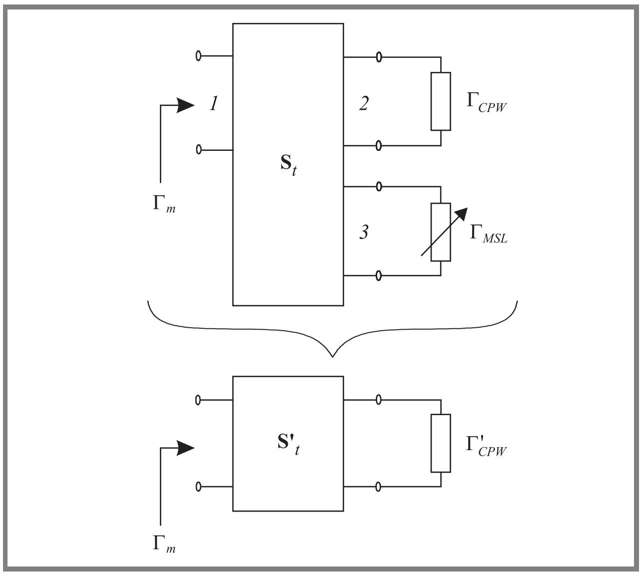

Fig. 6. Analysis method for one-port devices.

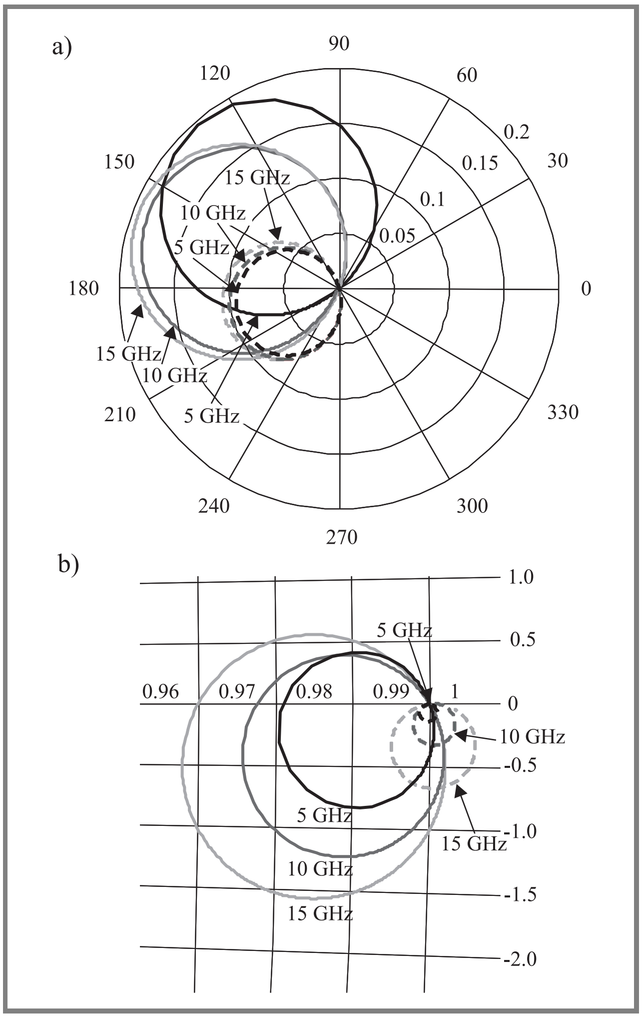

Fig. 7. Loci of $|\Gamma_{MSL}| = 1$ in the plane of the de-embedded reflection coefficient Γ'_{CPW} for (a) a matched load ($\Gamma_{CPW} = 0$), and (b) an open circuit ($\Gamma_{CPW} = 1$), for ISS (- - -) and GaAs (——) substrate.

Due to bilinear relationship between Γ_m and Γ_{MSL}, the deviations are constrained by the locus circle $|\Gamma_{MSL}| = 1$ in the complex Γ'_{CPW} plane. Such loci are presented in Fig. 7 in polar coordinates for a matched load and an ideal open circuit, at three frequencies: 5, 10, and 15 GHz and for both substrates (see Table 1). As it can be seen, the multimode propagation errors may have considerable effects, especially in case of the matched load. In both cases the errors are bigger for the GaAs substrate than for the ISS substrate, which can be justified with a higher transmission on the MSL mode in case of the GaAs substrate (see Fig. 4b). Furthermore, the error increases with frequency, which may be explained with an increasing transmission on the MSL mode seen in Fig. 4b.

3.2. CB-CPW transmission line section

In this section we investigate multimode propagation errors in case of a section of the CB-CPW transmission line. To this end we examine the impact of the parasitic MSL mode transmission on the measurement of the line parameters for the CPW mode. The basic idea of our method is shown in Fig. 8.

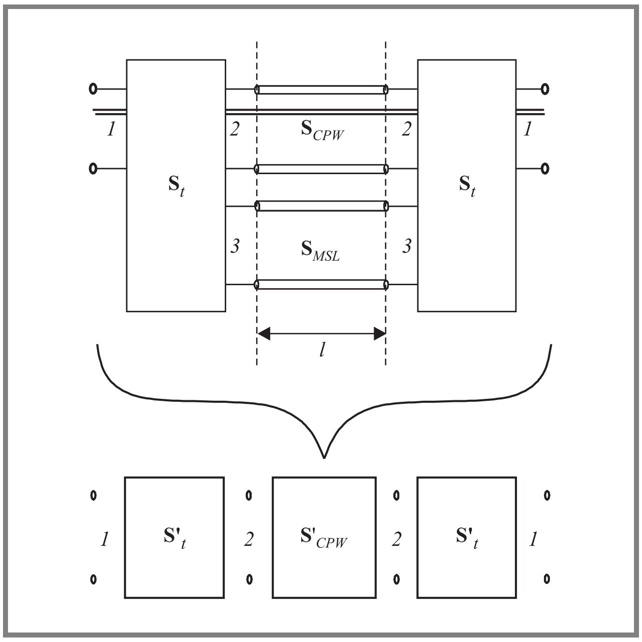

Fig. 8. Analysis method for the CB-CPW line section.

To simulate the measurement of a section of a multimode lossless CB-CPW line, we describe propagation for the CPW and MSL mode with scattering matrices:

$$\mathbf{S}_{CPW} = \begin{bmatrix} e^{-j\beta_{CPW} l} & 0 \\ 0 & e^{-j\beta_{CPW} l} \end{bmatrix}, \tag{2a}$$

$$\mathbf{S}_{MSL} = \begin{bmatrix} e^{-j\beta_{MSL} l} & 0 \\ 0 & e^{-j\beta_{MSL} l} \end{bmatrix}, \tag{2b}$$

where β_{CPW} and β_{MSL} are propagation constants of the CPW and MSL mode, respectively, determined from the 3D EM simulations, and l is the line length. In the measurement we obtain two-port S-parameters $\mathbf{S}_m$, which are different from the parameters $\mathbf{S}_{CPW}$ of the CPW line because of the systematic errors introduced by the probe and parasitic transmission over the MSL mode. From $\mathbf{S}_m$, we de-embed matrix $\mathbf{S}'_{CPW}$ of the CPW line employing previously determined two-port probe description with matrix $\mathbf{S}'_t$. For this purpose we apply the wave transmission matrix notation utilising the following relationship:

$$\mathbf{T}'_{CPW} = \mathbf{T}'^{-1}_t \mathbf{T}_m \overline{\mathbf{T}'_t}^{-1}, \tag{3}$$

where $\mathbf{T}'_{CPW}$, $\mathbf{T}'_t$ and $\mathbf{T}_m$ are the transmission matrices corresponding to relevant scattering matrices, and $\overline{\mathbf{T}'_t}$ denotes the matrix of the reversely connected two-port $\mathbf{T}'_t$.

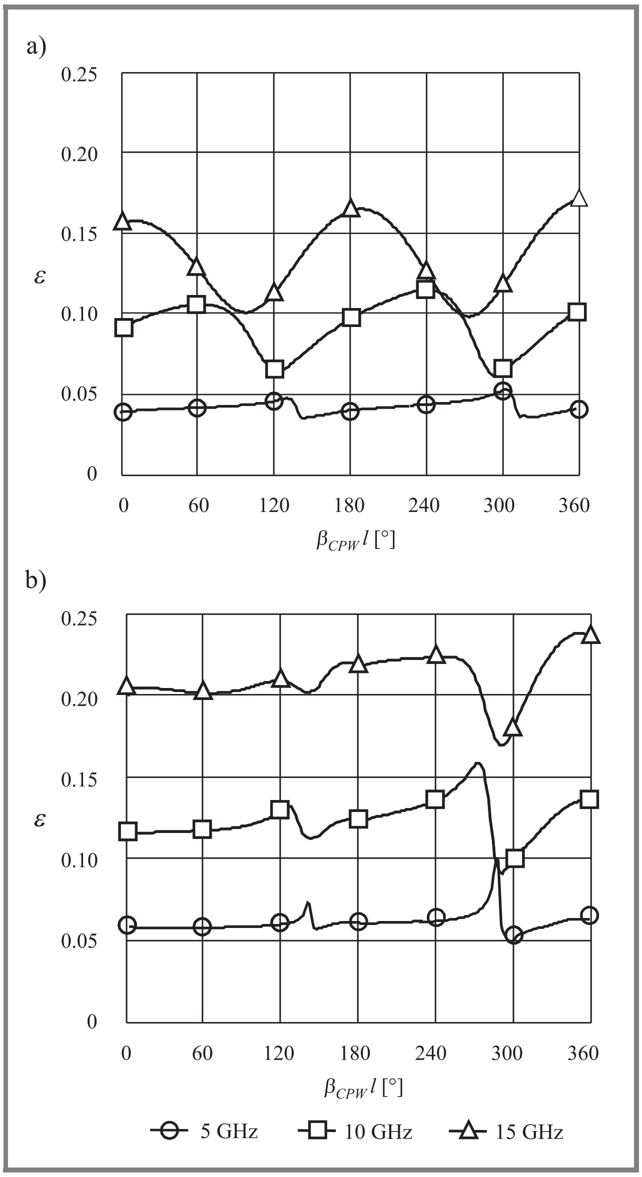

Fig. 9. Worst case error ε due to multimode propagation in a measurement of CPW line S-parameters as a function of CPW line electrical length for (a) ISS and (b) GaAs substrate.

Subsequently, with (3) we calculate the worst case deviation between the actual and de-embedded parameters of the CPW line, defined as:

$$\varepsilon = \max_{i,j} \left| S'_{CPW,ij} - S_{CPW,ij} \right| . \qquad (4)$$

Results of our simulations for the ISS and GaAs substrate for different line lengths are shown in Fig. 9. The worst case error ε is presented as a function of the CPW electrical line length at three frequencies: 5, 10 and 15 GHz. As it can be can seen in Fig. 9, the error caused by multimode propagation is significant. Its dependence on the line length reveals some ripples that may be explained with the interference of both modes each having own phase velocity (see Fig. 2). Growth of the errors in frequency can be attributed to the increase of the MSL mode transmission seen in Fig. 4. Furthermore, comparison between Fig. 9a and Fig. 9b shows that the multimode propagation error is higher for the GaAs substrate, which corresponds well with the higher transmission of the MSL mode for this substrate (see Fig. 4b).

4. Conclusions

We have presented for the first time a systematic analysis of errors occurring in on-wafer measurement of typical CPW elements due to the presence of the parasitic MSL mode in substrates with a backside metallisation. We determined the upper bound for these errors in measurements of some exemplary one- and two-port devices. Our analysis consisted of two steps.

At first we characterized a transition between an air-coplanar probe and a CB-CPW line using 3D EM simulations. We took into account two types of substrates: the ISS calibration substrate and a typical MMIC GaAs substrate. In both cases our results revealed significance of the parasitic MSL mode in comparison with the transmission on the main CPW mode. We utilised results of the EM simulations to model the transition as a multimode three-port.

In the next step we applied the model to assess the errors due to the parasitic MSL mode by mimicking the conventional single-mode measurement procedure typically used for characterisation of CPW devices. To this end, we examined a matched load, an ideal open circuit, and CB-CPW transmission line section as the most frequently used exemplary circuits. We studied errors in de-embedding of their *S*-parameters from simulated measurements under varying circuit conditions for the MSL mode. Assuming passive response of the MSL circuit, we determined upper bounds for the errors in the measurements of these CPW devices.

Our analysis reveals that the errors caused by the parasitic MSL mode may seriously deteriorate measurements, especially for CPW loads and lines. This in turn may have a significant impact on both CB-CPW-based calibration and de-embedding procedures. In consequence, the design reliability of CB-CPW-based circuits, e.g., MMICs, may suffer much.

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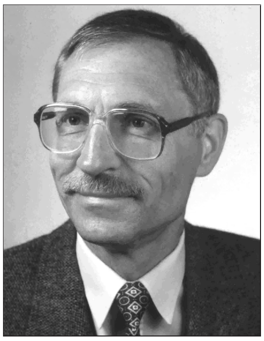

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