Thru-Load De-embedding Method for Millimeter Wave Transmission Lines

Vipin Velayudhan, Ayssar Serhan, Nicolas Corrao, Emmanuel Pistono, Jean-Daniel Arnould
University of Grenoble-Alpes
Laboratory IMEP–LAHC, UMR 5130 INPG-UJF-CNRS
Grenoble, France
{vipisv, ayssarserhan}@gmail.com, {corraon, emmanuel.pistono, jean-daniel.arnould}@minatec.inpg.fr

***Abstract*—This paper presents a new deembedding method for transmission lines at millimeter waves and beyond in silicon integrated technology. The proposed method is called "Thru-Load" de-embedding which is a simplification from "Half-Thru" de-embedding. In this method the pad or pad interconnects parasitics are modeled into a simple "Half-Thru". The simulated and measurement results are presented for the fabricated S-CPW transmission line as device under test in Bi-CMOS 55 nm technology.**

Keywords—De-embedding; millimeter wave; characterization; integrated circuits; S-CPW transmission line.

I. INTRODUCTION

RF/Microwave industries and researchers are developing millimeter wave applications in each and every domain, such as telecommunications (57-66 GHz), automotive radar (76-81 GHz), imaging (around 140 GHz, 220 GHz, …), etc.. The development of silicon technologies promises many advantages such as low manufacturing cost, a high integration density and low power consumption for integrated devices at millimeter wave and beyond. To ensure the best performance, these devices have to be measured and characterized before its implementation on the circuits or systems [1].

Generally, the silicon based devices are characterized on-wafer with the help of probe station and vector network analyser. The devices include additional parasitics from the pad and interconnecting lines that are used to connect until the device. These additional parasitics affects the original characteristics of the devices, thus it should be subtracted from the measured results to get the intrinsic characteristics of the device. This process of mathematically removing the unwanted parasitic effects is called "De-embedding" [2]. However we can obtain a good calibration until the probe tips using LRRM (Line-Reflect-Reflect-Match) method [3]. After the calibration a de-embedding step should be performed.

Currently, there are different de-embedding methods available from few "GHz" to about 170 GHz. However, only few methods are analyzed and work beyond or at millimeter wave band [1]-[6]. All these methods are limited to the frequency range or accuracy of the de-embedding. Previous studies show TRL is the best method that works for millimeter wave [4]. However, TRL need to know the value of characteristic impedance of the *line*(*s*) de-embedding structure to set the reference plane as well as it is band limited according to the length of the line, which covers only 1:8 of the frequency range. So, a new method called Thru-Load de-embedding which is a simplification from Half-Thru de-embedding method is proposed and analysed [2], [6].

II. THRU-LOAD DE-EMBEDDING

A. Theory

Thru-Load de-embedding is uses a measured *Thru* de-embedding structure instead of the two *lines* to calculate the *Thru* [6]. The measurement model of the S-CPW transmission line as device under test (DUT) to perform the Thru-Load de-embedding is shown in Fig. 1.

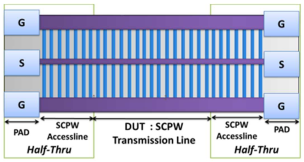

Fig. 1. Measurement model of S-CPW as DUT

In Thru-Load de-embedding method, the parasitics are modeled in to single error box named as "Half-Thru". We recommend using accesslines to connect the DUT for good electromagnetic continuity in front of the DUT. By considering the transfer functions of the *Thru* and *Load* de-embedding structures, we can obtain the Half-Thru. The obtained scattering parameters of the Half-Thru can be written as,

$$S_{22} = \frac{S_{11L} - S_{21T}.\Gamma_{Load} - S_{11T}}{S_{11L}.\Gamma_{Load} - S_{11T}.\Gamma_{Load} - S_{21T}} \tag{1}$$

$$S_{21} = S_{12} = \sqrt{S_{21T}.(1 - S_{22}^2)} \tag{2}$$

$$S_{11} = S_{11T} - S_{21T}.S_{22} \tag{3}$$

The '*L*' and '*T*' in the equations indicate the known *Load* and measured *Thru*. It is important to use a load value which is different from the Z_c of the pad/interconnecting line to determine the Half-Thru. Here we use the Z_{Load} of 100 Ω loaded at "Half-Thru", considering the $Z_c$of the accessline that is 50 Ω. The load value should be known to determine the

978-1-5090-4412-2/17/$31.00 ©2017 IEEE

Half-Thru. Here we use the open de-embedding method to extract the load value by considering *Load* as DUT. The method uses only "*open*" de-embedding structure. The load value can be extracted by using the following equation,

$$Z_{Load} = (Y_{DUT\ measure} - Y_{Open})^{-1} \quad (4)$$

Where, $Y_{\text{DUT measure}}$ is the admittance matrix of the *Load* DUT measured with the pad parasitics and Y_{Open} is the measured *open* de-embedding structure.

III. SIMULTION AND MEASYRED RESULTS

The S-CPW transmission line with $Z_c$of 50 Ω and the all the de-embedding structures are in Bi-CMOS 55 nm technology. The measurements are performed until 150 GHz with the help of probe station and VNA at IMEP-LAHC. The de-embedded results are presented in the Fig. 2 and Fig. 3 respectively.

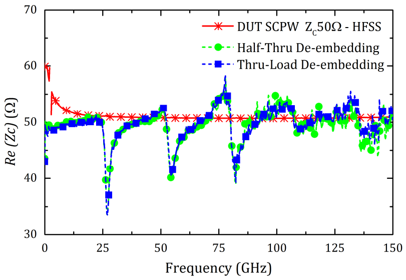

Fig. 2. Characteristic impedance (Z_C) vs Frequency

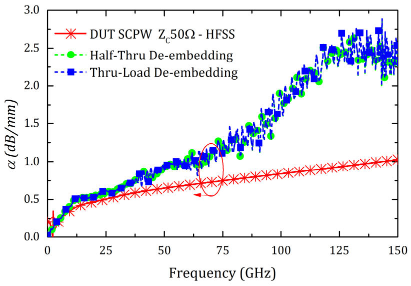

Fig. 3. Attenuation coefficient (α) vs Frequency

The characteristic impedance (Z_c) and the attenuation coefficient (α) are compared for Half-Thru de-embedding and simulated S-CPW line using Ansys HFSS v15. However TRL needed the line impedance to set the reference point, considering DUT itself is a transmission line. In addition, the previous results show that the Half-Thru de-embedding and Thru-Load de-embedding are comparable with TRL [2]. Half-Thru de-embedding and Thru-Load de-embedding show very good agreement with the simulated S-CPW transmission line until 150 GHz for Z_c. However the α of S-CPW shows an excessive losses beyond 60 GHz. This is due to additional propagation happening with the adjacent cells in the wafer (see Fig. 4) and measurement probes which is explained based on a realistic EM simulation model in [2]. Considering this is an on-wafer measurement problem only Z_c is used to explain the accuracy.

In conclusion, the method has very good accuracy because it does not have any approximations and unknown parameters. In addition, the method is less costly (less number of de-embedding structures) for the wide band, which is a great advantage over other methods. Compared to TRL it takes only half of the place, considering the *line*(*s*) de-embedding structures not required, which reduces more than 50% the area.

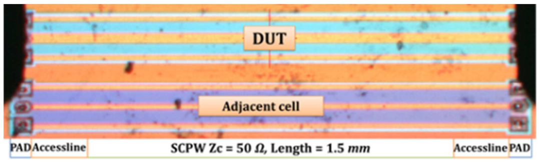

Fig. 4. Fabricated S-CPW DUT with adjacent cells

IV. CONCLUSION AND PERSPECTIVE

A new de-embedding called Thru-Load de-embedding method is presented with promising results at millimeter wave in Bi-CMOS 55 nm silicon technology. The simulated and measured results are explained by considering S-CPW transmission line as DUT until 150 GHz. Thru-Load de-embedding has very good accuracy with no-unknown parameters, no band limitations and less number of de-embedding structures which eventually reduces the cost by more than 50%.

ACKNOWLEDGMENT

The work presented here has been performed in the RF2THZ SiSoC project of the EUREKA program CATRENE in which the French partners are funded by the DGCIS. In addition, this work is supported by BISCIG (Build n Self Characterization in G Band) by ANR and IMEP-LAHC.

REFERENCES

[1] O. El. Bouayadi, "Module wireless 60 GHz intégré en 3D sur silicium. Electronique", Ph.D. dissertation, *Micro and nanotechnologies/Microelectronics*, Université Grenoble Alpes, France, 2016.

[2] V. Velayudhan, "Vectorial measurement methods for millimeter wave integrated circuits", Ph.D. dissertation, *Micro and nanotechnologies/Microelectronics*, Université Grenoble Alpes, France, 2016.

[3] D. F. Williams and R. B. Marks, "Calibrating On-Wafer Probes to the Probe Tips," in *ARFTG Conference Digest-Fall, 40th*, vol. 22, pp. 136–143, 1992.

[4] G. F. Engen and C. A. Hoer, "Thru-Reflect-Line: An Improved Technique for Calibrating the Dual Six-Port Automatic Network Analyzer," *IEEE Trans. Microw. Theory Tech*., vol. 27, no. 12, pp. 987–993, Dec. 1979.

[5] B. Zhang, Y. Xiong, L. Wang, S. Hu, and J. L.-W. Li, "On the De-Embedding Issue of Millimeter-Wave and Sub-Millimeter-Wave Measurement and Circuit Design," *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 2, no. 8, pp. 1361–1369, 2012.

[6] V. Velayudhan, E. Pistono, and J.-D. Arnould, "Half-Thru de-embedding method for millimeterwave and sub-millimeter-wave integrated circuits," in *Microelectronics and Electronics (PRIME), 2014 10th Conference on Ph.D. Research in*, pp. 1–4., Jul. 2014.