Investigation of De-embedding Techniques Applied on Uni-Traveling Carrier Photodiodes

Citation for published version (APA):

Konstantinou, D., Caillaud, C., Rommel, S., Johannsen, U., & Monroy, I. T. (2021). Investigation of De-embedding Techniques Applied on Uni-Traveling Carrier Photodiodes. In *2020 50th European Microwave Conference, EuMC 2020* (pp. 320-323). [9338063] Institute of Electrical and Electronics Engineers. <https://doi.org/10.23919/EuMC48046.2021.9338063>

DOI:

[10.23919/EuMC48046.2021.9338063](https://doi.org/10.23919/EuMC48046.2021.9338063)

Document status and date:

Published: 02/02/2021

Document Version:

Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Investigation of De-embedding Techniques Applied on Uni-Traveling Carrier Photodiodes

Dimitrios Konstantinou^{#1}, Christophe Caillaud^{*2}, Simon Rommel^{#3}, Ulf Johannsen^{#4}, Idelfonso Tafur Monroy^{#5}

[#]Eindhoven University of Technology, 5600MB Eindhoven, Netherlands

^{*}III-V Lab, a joint Lab from Nokia, Thales and CEA, 91767 Palaiseau Cedex, France

{¹d.konstantinou, ³s.rommel, ⁴u.johannsen, ⁵i.tafur.monroy}@tue.nl, ²christophe.caillaud@3-5lab.fr

Abstract— This work reviews and investigates two de-embedding methods contributing to the characterization of the active region within uni-traveling carrier photodiodes. De-embedding techniques remove the parasitic effects of the waveguides connected to the active area of these devices allowing the calculation of their series resistance and junction capacitance. The Open-Short method is examined where a systematic error introduced by the technique is identified. This error is analytically extracted and a correction is implemented. The properties of an S-Parameter based de-embedding are also analyzed through simulation approaches. The lumped components calculated and verified by these processes are compared for diodes with different sizes.

Keywords— de-embedding, UTC-PDs, microwave photonics.

I. INTRODUCTION

5G hybrid photonic-wireless links operating in the lightly licensed millimeter wave (mm-wave) bands will be capable of supporting high-speed connections to a massive amount of end users with high capacity, guaranteed quality of service and ultra-low latency [1]. The convergence between optics and electronics will take place within future 5G base stations entailing high speed photodiodes that convert optical signals to mm-waves and transmit them in the RF domain [2].

One example of a high-speed photodetecting device is a uni-travelling carrier photodiode (UTC-PD). Within UTC-PDs, electrons are the only active carriers providing increased sensitivity, broad bandwidth and high saturation power. A block diagram of the overall structure of a UTC-PD is presented in Fig. 1. The photon absorption and carrier generation takes place at a thin layer where the holes are directly swept to the P-Contact. A diffusion block layer supports the unidirectional motion of electrons from the absorber to the collector and then to the N-contact [3]. The measurement of the junction capacitance C_j and series resistance R_s of the active region within the diodes is of utmost importance since they provide crucial information about their RC-Bandwidth as well as revealing if there was a process issue on the wafer where the diode chips are fabricated.

The calculation of both C_j and R_s can be achieved by lumped component simulations while removing the parasitic effects added by the transmission lines (TML) attached to them by using different de-embedding techniques. In this article, we analyse the method described by M.C.A.M. Koolen in [4] and demonstrate that it introduces a systematic error for single pole devices. Then, we show that an alternative S-Parameter

Fig. 1. A UTC-PD capable of generating current at its load (R_L) due to the creation of electron-hole pairs by the absorption of photons with energy hf .

based method presented in [5] produces very accurate results on various UTC-PDs.

II. MODELLING OF UTC PHOTODIODES

In the electrical domain, a UTC-PD can be considered as a single-port device with a TML connected to its active region. As illustrated in Figure 2a), the landing pads of the TML allow a probe to land on its surface so that reflection coefficient measurements can be conducted with a VNA where Γ_m is obtained. If the S-Parameters of the TML $S_{TML} = [S_{ij}], i, j = \{1, 2\}$ are known, then the reflection coefficient of the active region within the UTC-PD (Γ_{UTC-PD}) can be extracted analytically based on (1).

Fig. 2. a) The active region of an on-wafer UTC-PD connected to waveguide pads that need to be de-embedded; b) The short and open circuit waveguides.

$$\Gamma_{UTC-PD} = \frac{S_{11} - \Gamma_m}{S_{11}S_{22} - S_{22}\Gamma_m - S_{12}S_{21}} \quad (1)$$

However, the TML characteristics are not always easy to acquire and thus de-embedding techniques are employed. The principle of de-embedding is to achieve the mathematical extraction of the Γ_{UTC-PD} based on measurement of the TML terminated by an open (open test structure, Γ_{OC}) and by a short circuit (short test structure, Γ_{SC}). The block diagrams of these structures are depicted in Fig. 2b). The de-embedded

reflection coefficients are imported to an ADS circuit model where the lumped elements C_j and R_s are obtained by using its optimization feature that is capable of minimizing the error difference $\epsilon = |\Gamma_{UTC-PD} - \Gamma_{model}| / |\Gamma_{UTC-PD}|$ between the extracted data and the model.

III. THE OPEN-SHORT DE-EMBEDDING METHOD

The Open-Short method introduced by Koolen is based on the conversion of all measured S-parameters into admittances (Y) and calculates the impedance of a device under test (DUT) by implementing (2). This technique is applied to a $5 \times 25 \mu m^2$ UTC-PD and the Smith chart of Fig. 3 is obtained. Both Γ_{SC} and Γ_{OC} contribute to the curvature of Γ_m . It is evident that the parasitics introduced by the waveguide are removed at the de-embedded (red) curve.

$$Z_{Koolen} = (Y_m - Y_{OC})^{-1} - (Y_{SC} - Y_{OC})^{-1} \quad (2)$$

Fig. 3. The impact of the Open-Short method on a $5 \times 25 \mu m^2$ UTC-PD leading to the removal of the waveguide parasitics at $-2 V$ reverse bias.

Ideally, it is expected that $Z_{Koolen} = Z_{UTC-PD}$. However, as shown in Fig. 4a), in order to acquire a perfect optimization in ADS, a series inductor (L_p) needs to be added to the de-embedded equivalent contradicting with the predicted circuit model of the active area within a UTC-PD. The origin of L_p is thoroughly investigated in the following section.

A. Investigation of the Inductive Behavior Introduced by the Open-Short Technique

To prove the existence and magnitude of the additional inductance, the Open-Short de-embedding is studied analytically in the case where a random DUT is connected to a low-loss TML with length l . This TML is based on the distributed model with a transfer matrix given in (3) [6], having a propagation constant $\gamma = \sqrt{zy}$ and lumped elements equal to $z = R + j\omega L \approx j\omega L$, $y = G + j\omega C \approx j\omega C$. Finally, $Z_c = \sqrt{z/y}$ is the characteristic impedance of the line. Each variable is measured in units per unit length.

$$T = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & Z_c \sinh(\gamma l) \\ \frac{\sinh(\gamma l)}{Z_c} & \cosh(\gamma l) \end{bmatrix} \quad (3)$$

$$Z_m = \frac{AZ_{DUT} + B}{CZ_{DUT} + D}, Z_{OC} = \frac{A}{C}, Z_{SC} = \frac{B}{D}$$

Converting the impedances in (3) to admittances through inversion and replacing them in (2) result in (4).

$$Z_{Koolen} = Z_{DUT} \cosh^2(\gamma l) \quad (4)$$

The Taylor approximation of $\cosh^2(\gamma l)$ leads to,

$$Z_{Koolen} = \frac{1}{2} Z_{DUT} \left[1 + \sum_{n=2}^{\infty} \frac{(2\gamma l)^{2n}}{(2n)!} \right] \approx Z_{DUT} [1 + (\gamma l)^2] \quad (5)$$

If the products $L \times l$ and $C \times l$ are in the range of $(10^{-12} H)$ and $(10^{-15} F)$ respectively, the residual error of the Taylor expansion $R_2 = \sum_{n=2}^{\infty} (-1)^n (10)^{-9n} [\frac{2^{2n}}{(2n)!}]$ can be omitted since it is in the range of 10^{-18} . If the DUT is a UTC-PD, the result of (5) agrees with Fig. 4a) since $Z_{Koolen} \neq Z_{UTC-PD}$. By placing $Z_{UTC-PD} = R_s - j \frac{1}{\omega C_j}$ in (5), and omitting the real parasitic term $|R_s(\gamma l)^2| < 1 m\Omega$, equation (6) is obtained.

$$Z_{Koolen} = Z_{UTC-PD} + j\omega \frac{LC}{C_j} l^2 \quad (6)$$

Consequently, an additional inductance ($L_p = \frac{LC}{C_j} l^2$) is calculated that depends on the characteristics of the transmission line (L, C, l) while it is inverse proportional to the junction capacitance. The exact same result for L_p is measured if the equation of the Open-Short method is implemented for the Pi and T equivalent models of a transmission line [7]. This process proves that a systematic error is added to the extraction of Z_{DUT} while using the Open-Short de-embedding technique.

To verify these analytical calculations, the additional inductance is extracted in ADS based on experimental data for diodes with different sizes and reverse bias applied. Theoretically, the value of $C_j = \epsilon A_j / l_j$ is proportional to the junction area (A_j). In Fig. 4b), L_p is plotted as a function of increasing A_j for different measured diodes at a bias of $-2 V$. The decreasing junction area of a UTC-PD reduces the value of C_j while it increases L_p . Then, a hyperbolic curve fitting is used in order to show the inverse proportionality of L_p to the sizes of the diodes while $LC l^2$ is constant.

In order to remove the additional inductive behavior of (6), a correction to the Open-Short technique needs to be introduced isolating Z_{UTC-PD} . Therefore, the term $\cosh^2(\gamma l)$ in (4) will be expressed as a function of the two known variables imported from the open (Y_{OC}) and short (Y_{SC}) structures. Calculating $Y_{OC} + Y_{SC}$, as well as using the hyperbolic trigonometric identities and (4), results in (7) which introduces a correction and forms an impedance based de-embedding capable of removing the systematic error imported in (2) for any single-port based DUT.

$$Z_{Corrected} = Z_{OC} \frac{Z_m - Z_{SC}}{Z_{OC} - Z_m} \quad (7)$$

The de-embedded Smith charts of the same $5 \times 25 \mu m^2$ diode are presented in Fig. 4(c) while implementing the Open-Short method and its correction. The curves overlap; however, the Smith chart of the Open-Short is longer due to L_p added by the method itself. Consequently, equation (7) is able to isolate the active region of a UTC-PD leading to the valid design of its circuit model.

Fig. 4. a) The resulting equivalent circuit extracted by the Open-Short method; b) the L_p introduced by the Open-Short technique as a function of area at a reverse bias voltage of -2 V for different UTC-PDs; c) the difference of the S-parameters between the Open-Short and corrected methods showing the L_p .

Fig. 5. The impact of the S-Parameter based method to a $5 \times 25 \mu m^2$ UTC-PD leading to the removal of the waveguide parasitics at -2 V reverse bias.

IV. THE S-PARAMETER BASED DE-EMBEDDING METHOD

An alternative to the Open-Short de-embedding is an S-Parameter based (SPb) technique and primarily focuses on the reduction of the unknown variables of the S_{TML} in (1) from four to two. This is achieved by firstly applying the property of passive behaviour of the TML connected to the UTC-PD where $S_{12} = S_{21}$. Furthermore, it is assumed that the TML is symmetric leading to $S_{11} = S_{22}$. This is a crucial hypothesis that needs to be further investigated. The final equation is derived in (8) as a function of Γ_m , Γ_{OC} and Γ_{SC} by replacing and rearranging the variables in (1) from the data obtained for the open structure, $\Gamma_{DUT} = 1$, $\Gamma_m = \Gamma_{OC}$ and for the short $\Gamma_{DUT} = -1$, $\Gamma_m = \Gamma_{SC}$.

$$\Gamma_{SPb} = \frac{\Gamma_{OC} + \Gamma_{SC} - 2\Gamma_m - \Gamma_m(\Gamma_{OC} - \Gamma_{SC})}{2\Gamma_{OC}\Gamma_{SC} + \Gamma_{SC} - \Gamma_{OC} - \Gamma_m(\Gamma_{OC} + \Gamma_{SC})} \quad (8)$$

The Smith chart of Fig. 5 demonstrates the impact of the S-Parameter based method on a $5 \times 25 \mu m^2$ UTC-PD. As it is achieved with the Open-Short technique and its correction, the waveguide parasitics are removed in the curve of Γ_{SPb} .

A. Evaluating the Assymetry Assumption for the TML

The S-Parameter based technique is based on the assumption that the transmission lines that are connected to the devices under test are symmetric, i.e., $S_{11} = S_{22}$.

Consequently, it is essential to test this hypothesis in order to predict the errors that are introduced in the de-embedding processes. The error estimation is achieved by using the features provided in ADS.

A photodiode connected to a transmission line is designed with lumped components in Fig. 6a). The TML is based on the Pi model that is fully symmetric if $C_{TML1} = C_{TML2}$ (therefore $S_{11} = S_{22}$). Asymmetry can be introduced by setting $C_{TML2} = (1 - a)C_{TML1}$ where a is a factor varying between 0 to 100 %. The values of the lumped components for these simulations are shown in red color and are based on measurements of a $5 \times 25 \mu m^2$ UTC-PD. The S parameters of the TML terminated by a short (Γ_{SC}) and by an open circuit (Γ_{OC}) are also simulated to reproduce the test structures on a real wafer. Additionally, ADS is used to calculate the S_{TML} .

The impact of the asymmetry on the de-embedded circuits is tested by implementing both the equations (1) and (8) which gives the exact values of C_j and R_s . The first figure of merit that is tested is the effect of the asymmetry on the S_{11} and S_{22} parameters of the TML. Therefore, $\Delta S_{TML} = |S_{11} - S_{22}|/S_{11}$ is introduced comparing the magnitude of the reflection coefficient S_{11} to S_{22} . The ΔS_{TML} is calculated for an ascending value of the asymmetry factor a . The results are provided in Fig. 6b) where it is evident that the asymmetry of a transmission line affects its S-parameters.

Figure 6c) shows the percentage of difference between the junction capacitance (C_j) and series resistance (R_s) calculated by the S-Parameter based method and the original values as a function of the increasing asymmetry. The curves are linear and for 100 % of asymmetry the difference reaches 7.1 % for C_j and 8.2 % for R_s . Similar behavior is demonstrated in the percentage differences in the mean values of magnitude, phase, real and imaginary parts of the diode's reflection coefficients (Γ_{UTC-PD}). Based on the analysis above, the transmission line symmetry influences the S-parameters (Γ_{SPb}) of the de-embedded circuits as well as the values of the lumped components C_j and R_s . However, the percentage of difference does not exceed the 8.2 % for all the tested variables. Since there is not an effective divergence between the de-embedded values and the original data, it can be deduced that the S-Parameter based method poses an alternative de-embedding technique for the removal of the TML from a DUT.

Fig. 6. a) A lumped component simulation of a UTC-PD connected to a transmission line based on the Pi model; b) ΔS_{TML} as function of frequency for different asymmetry values; c) The percentage difference of C_j , R_s and of the characteristic properties of Γ_{UTC-PD} between the S-Parameter based and direct methods as a function of the increasing TML asymmetry.

Table 1. Comparison of C_j and R_s Between the Extracted De-embedded Equivalent Circuits

Diodes at Reverse Bias of -2 V Simulation Based Equivalent	$4 \times 10\ \mu\text{m}^2$		$4 \times 20\ \mu\text{m}^2$		$5 \times 25\ \mu\text{m}^2$		$7 \times 25\ \mu\text{m}^2$	
	C_j [fF]	R_s [Ω]	C_j [fF]	R_s [Ω]	C_j [fF]	R_s [Ω]	C_j [fF]	R_s [Ω]
Open-Short	18.2	29.3	31.5	16.4	40.0	13.2	58.1	9.5
Open-Short Corrected	18.0	26.3	30.7	14.4	39.2	11.6	55.9	8.3
S-Parameter based	18.1	26.3	30.7	14.4	39.3	11.6	56.0	8.3

B. Comparison Between De-embedding Methods

The Corrected method is compared with the S-Parameter based one in order to define the differences between the resulting C_j and R_s . By superimposing the de-embedded S-parameter curves ($\Gamma_{Corrected}$, Γ_{SPb}) of Fig. 4c) and Fig. 5 on a Smith chart, the curves overlap. That is due to the fact that both the techniques in (7) and (8) are extracted based on the symmetry of the transmission lines. With further investigation and by implementing the conversion equation from Z to S parameters [8], the corrected method becomes identical to the S-Parameter based. Therefore, the two de-embedding processes converge and can be expressed in different parameters.

In Tab. 1 a full comparison is shown between C_j and R_s for diodes with different sizes while implementing the three de-embedding techniques. As expected, the differences in the lumped element values between the Corrected and the S-Parameter based are negligible. Furthermore, the percentage of error difference between the Koolen technique and the other two equations increases as a function of size not exceeding 3.8 % for C_j and 12.6 % for R_s which is moderate but significant. Thus, the classical method by Koolen offers good value estimation of R_s and C_j at the price of adding a virtual inductance leading to an imprecise circuit model of the active region within the photodiodes. This can be corrected by the two improved methods described in this work providing a more accurate equivalent for analyzing the properties of UTC-PDs.

V. CONCLUSION

This paper evaluates the extraction methods of the junction capacitance and series resistance of UTC-PDs by deploying de-embedding processes and performing lumped component simulations based on experimental measurements. More specifically, the Open-Short and the S-Parameter based de-embedding techniques capable of removing the parasitic effects added by the waveguides connected to the UTC-PDs

are analyzed. A systematic error added by the Open-Short technique is observed and thoroughly studied leading to the derivation of an updated equation that removes its impact. Furthermore, the assumptions made defining the S-Parameter based equation are tested. Simulations conducted calculating the significance of these assumptions provide satisfactory results since minimal error is introduced. While all the de-embedding methods studied may be reliable candidates, the proposed correction minimizes the error introduced in modeling the characteristic features of UTC-PDs which offer a unique solution for interfacing the optical with the RF domain.

ACKNOWLEDGMENT

This work was partially funded by the 5G STEP FWD, 5G-PHOS and blueSPACE projects with funding from the European Union's Horizon 2020 research and innovation programme under grant agreement numbers 722429, 761989, and 762055, respectively.

REFERENCES

- [1] D. Konstantinou *et al.*, "5G RAN architecture based on analog radio-over-fiber fronthaul over UDWDM-PON and phased array fed reflector antennas," *Optics Communications*, vol. 454, Jan. 2020.
- [2] A. Morales *et al.*, "Bidirectional K-Band Photonic/Wireless Link for 5G Communications," in *IRMMW-THz*, Sep. 2019, pp. 1–2.
- [3] T. Ishibashi *et al.*, "Uni-Traveling-Carrier Photodiodes," in *Ultrafast Electronics and Optoelectronics*. OSA, 1997, p. UC3.
- [4] M. C. A. M. Koolen, "On-wafer high-frequency device characterization," in *ESSDERC '92*, Sep. 1992, pp. 679–686.
- [5] H. Xu and E. Kasper, "A de-embedding procedure for one-port active mm-wave devices," in *SiRF*, Jan 2010, pp. 37–40.
- [6] A. Kallio and T. Veijola, "Synthesis of reduced equivalent circuits for transmission lines," *IEEE Trans. Circuits Syst. I*, vol. 53, no. 10, pp. 2255–2264, Oct 2006.
- [7] D. Pozar, *Microwave Engineering*, 4th Edition. Wiley, 2011.
- [8] D. A. Frickey, "Conversions between S, Z, Y, H, ABCD, and T parameters which are valid for complex source and load impedances," *IEEE Trans. Microw. Theory Techn.*, vol. 42, no. 2, pp. 205–211, Feb. 1994.