Improved Error Correction Technique for On-Wafer Lightwave Measurements of Photodetectors

P. Debie, L. Martens, and D. Kaiser

***Abstract*—An accurate correction technique for on-wafer small-signal lightwave measurements of photodetectors is presented. This technique is an improvement of the conventional calibration methods for on-wafer lightwave measurements. Mathematical expressions for the dominant error sources that exist in the measurement system are derived. Experimental results for an InGaAs–InP PIN photodiode show a smoother modulation response characteristic when the presented technique is used.**

I. Introduction

FOR the design and development of high-speed/high-frequency optoelectronic systems and circuits, efficient and accurate models of optoelectronic devices such as laser diodes, light emitting diodes, and photodiodes are required. Several models for this type of components have already been developed. Generally, the accuracy of these models depends on the accuracy of the measured characteristics of the device. Also, for the development of optoelectronic integrated circuits, one may want to compare the measured circuit behavior with theoretical calculations based on the characteristics of isolated devices [1]. Accurate measurements of the device characteristics are also required in this case.

This letter presents a de-embedding technique for on-wafer lightwave measurements of photodetectors. The technique takes more errors into account in order to improve the accuracy of previously reported methods [1]–[3]. Especially the consideration of multiple reflections between the photodetector output, the wafer probe input, and the non-ideal measurement system proves to be an important benefit of the presented technique compared to other currently used methods.

II. Correction Technique

The measurement system that is used for the characterization of the devices consists of a conventional HP8510B network analyzer that is extended with a HP83420A lightwave test set. In the lightwave test set, a 1.3 μm calibrated optical source is used for the electrical-to-optical conversion, and a 1.2–1.6 μm calibrated photodiode for the optical-to-electrical conversion. The output of the calibrated optical source can be modulated in intensity from 130 MHz to 20 GHz. A lightwave probe (LWP) of Cascade Microtech with a single mode lensed fiber is used to illuminate the on-wafer photodetector under test. The combined optical source/photodetector system is noninsertable, because it has a coaxial connector input and a coplanar output, and therefore we use a coplanar GSG wafer probe as an adapter to make the reverse transition. As in the case of conventional microwave network analyzer measurements, the measured lightwave characteristics have to be corrected in order to resolve them from the systematic errors that are inherent to any real measurement system. A technique that is commonly used for this type of measurements [3] is a simple response calibration. Although this technique is relatively fast and easy to implement, it is only accurate in the case of well matched, low loss devices. Because this is not true for most photodetectors, this technique is not accurate for making modulation response measurements. Also, because we are measuring a noninsertable device, a conventional response calibration cannot resolve the measured characteristics from the unwanted effects of the microwave wafer probe. A technique called adapter removal [4] can be a solution for this problem, but because this technique requires two full twoport calibrations, it is a much more cumbersome technique than the one we propose.

The signal flow graph of the measurement system, including the most important systematic errors, is presented in Fig. 1 for the case of an on-wafer photodetector as device under test. Reference plane 1 and reference plane 2 of Fig. 1 indicate the position of the reference planes after we use the presented correction technique. Reference plane 3 is an auxiliary plane which is necessary for de-embedding. E_{SF} and E_{LF} are the reflection error coefficients of the electrical source and load, respectively, and E_{TF} is the error coefficient for the attenuation of the transmission path. Due to the nature of the optoelectronic devices, the coefficient $S_{12}^{l+\mathrm{ph}}$ of the combined optical source/photodiode system can be neglected. This means that

$$S_{11}^{l+\mathrm{ph}} = S_{11}^{l} \tag{1}$$
$$S_{21}^{l+\mathrm{ph}} = S_{21}^{l} \cdot S_{21}^{\mathrm{ph}} \tag{2}$$
$$S_{12}^{l+\mathrm{ph}} = 0 \tag{3}$$
$$S_{22}^{l+\mathrm{ph}} = S_{22}^{\mathrm{ph}} \tag{4}$$

with superscript l referring to the calibrated optical source, superscript ph to the photodetector under test, and superscript $l+\mathrm{ph}$ to the combined optical source/photodiode system. The modulation response S_{21}^{ph} of the photodetector is defined as the ratio of the change in electrical output current to the change in incident optical power.

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P. Debie and L. Martens are with the University of Gent, Department of Information Technology, St.-Pietersnieuwstraat 41, 9000 Gent, Belgium.

D. Kaiser is with Alcatel SEL Research Centre, Department of Opto-Electronic Components ZFZ/WO, Lorenzstrasse 10, D-70435 Stuttgart, Germany.

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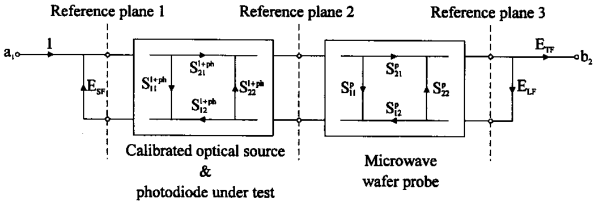

Fig. 1. Signal flow graph of the measurement system, including systematic errors.

If only the conventional response calibration of the lightwave test set is used for the measurement of the modulation response, the following five errors are neglected: mismatch of the electrical source output (E_{SF}) and the optical source input (S_{11}^{l}), mismatch of the photodetector output (S_{22}^{ph}) and the probe input (S_{11}^{p}), the attenuation (S_{21}^{p}) of the microwave probe, mismatch of the probe output (S_{22}^{p}) and the electrical receiver input (E_{LF}), and the error on the transmission coefficient ($E_{\mathrm{TF}}^{\mathrm{response}}$) of the response calibration. This means that the modulation response, measured with the conventional response calibration of the lightwave test set ($S_{21}^{\mathrm{response}}$), has to be corrected in order to take these errors into account. This leads to the following expression for the corrected modulation response of the photodetector (S_{21}^{ph})

$$S_{21}^{\mathrm{ph}} = \Gamma \cdot S_{21}^{\mathrm{response}} \tag{5}$$

with Γ a correction factor given by

$$\Gamma = \gamma^{s+l} \cdot \gamma^{\mathrm{ph}+p} \cdot \gamma^{p} \cdot \gamma^{p+rx} \cdot \gamma^{r}. \tag{6}$$

From the error model of Fig. 1, straightforward calculations result in the following expressions for the various error coefficients

$$\gamma^{s+l} = 1 - E_{\mathrm{SF}} \cdot S_{11}^{l} \tag{7}$$

for the electrical source output (E_{SF}) and optical source input (S_{11}^{l}) mismatch,

$$\gamma^{\mathrm{ph}+p} = 1 - S_{22}^{\mathrm{ph}} \cdot S_{11}^{p} \tag{8}$$

for the photodetector output (S_{22}^{ph}) and the probe input (S_{11}^{p}) mismatch,

$$\gamma^{p} = \frac{1}{S_{21}^{p}} \tag{9}$$

for the probe attenuation,

$$\gamma^{p+rx} = 1 - E_{\mathrm{LF}} \cdot \frac{S_{22}^{p} - S_{22}^{\mathrm{ph}} \cdot \det[S^{p}]}{1 - S_{11}^{p} \cdot S_{22}^{\mathrm{ph}}} \tag{10}$$

for the probe output (S_{22}^{p}) and receiver input (E_{LF}) mismatch, and

$$\gamma^{r} = \frac{E_{\mathrm{TF}}^{\mathrm{response}}}{E_{\mathrm{TF}}} = \frac{1}{1 - E_{\mathrm{SF}} \cdot E_{\mathrm{LF}}} \tag{11}$$

for the error on the transmission coefficient of the response calibration.

The electrical source and receiver, and the electrical input of the optical source in the lightwave test set are relatively well matched, so the error coefficients γ^{s+l} and γ^{r}—which are second order effects—can be neglected, and they are assumed to be equal to 1.

For the experimental determination of the remaining error correction factors (8)–(10), the twoport S-parameters of the wafer probe, the reflection coefficient of the photodiode, and the reflection coefficient of the receiver have to be determined. The S-parameters of the coplanar probe tip can be determined with the procedure described in [1], [2]. Using a full oneport calibration in reference plane 3 of Fig. 1, we measure the reflections at the coaxial side of the wafer probe which is terminated with three known on-wafer impedance standards (short, open, and load). Using these three measurements ($S_{22}^{\mathrm{short}}, S_{22}^{\mathrm{open}}$, and S_{22}^{load}) the S-parameters of the coplanar probe tip are determined using the following expressions

$$S_{22}^{p} = S_{22}^{\mathrm{load}} \tag{12}$$

$$S_{11}^{p} = \frac{S_{22}^{\mathrm{open}} + S_{22}^{\mathrm{short}} - 2 \cdot S_{22}^{\mathrm{load}}}{S_{22}^{\mathrm{open}} - S_{ss}^{\mathrm{short}}} \tag{13}$$

$$S_{21}^{p} \cdot S_{12}^{p} = -2 \cdot \frac{(S_{22}^{\mathrm{open}} - S_{22}^{\mathrm{load}}) \cdot (S_{22}^{\mathrm{short}} - S_{22}^{\mathrm{load}})}{(S_{22}^{\mathrm{open}} - S_{22}^{\mathrm{short}})}. \tag{14}$$

Using the same coaxial oneport calibration, now the reflection coefficient ($S_{22}^{\mathrm{ph},m}$) of the photodiode is measured at the coaxial side of the microwave probe (i.e., in reference plane 3). Using this measured value, and the S-parameters of the coplanar probe tip ((12)–(14)), the real reflection coefficient (S_{22}^{ph}) of the photodiode in reference plane 2 can be determined [1], [2]

$$S_{22}^{\mathrm{ph}} = \frac{S_{22}^{\mathrm{ph},m} - S_{22}^{p}}{S_{11}^{p} \cdot (S_{22}^{\mathrm{ph},m} - S_{22}^{p}) + S_{21}^{p} \cdot S_{12}^{p}}. \tag{15}$$

To complete, the reflection coefficient of the electrical receiver (E_{LF}) in reference plane 3 has to be determined. This coefficient can be measured with a second coaxial oneport calibration using the other port of the network analyzer, or more easily by reading one of the network analyzer's internal registers with the corresponding calibration error coefficient of the first oneport calibration. Now, we can use (8)–(10) to calculate the most dominant error coefficients. Equation (6) then results in the total error coefficient that corrects the modulation response measurement of the lightwave test set where only a conventional response calibration is provided. Although this technique is fairly easy to implement, up to now it has not yet been used to measure the modulation response of optoelectronic detector devices. A similar technique can also be used for the modulation response measurements of optoelectronic transmitter devices, but then the measurement set-up, and thus also the mathematical expressions for the error sources, will change [5].

III. Experimental Results

To demonstrate the improvement of this error correction technique, in comparison to the conventional methods, a planar InGaAs–InP pin-photodiode is characterized on-wafer at a reverse bias voltage V_{bias} of $-$ 2 V. For that purpose, in a first step the corrected output reflection coefficient of

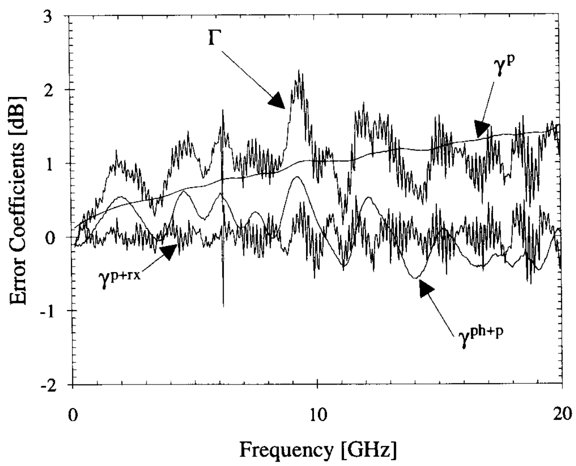

Fig. 2. Magnitude of the error coefficients γ^{ph+p}, γ^p, and γ^{p+rx}, and the total error coefficient Γ for an InGaAs–InP photodiode ($V_{bias} = -2$ V).

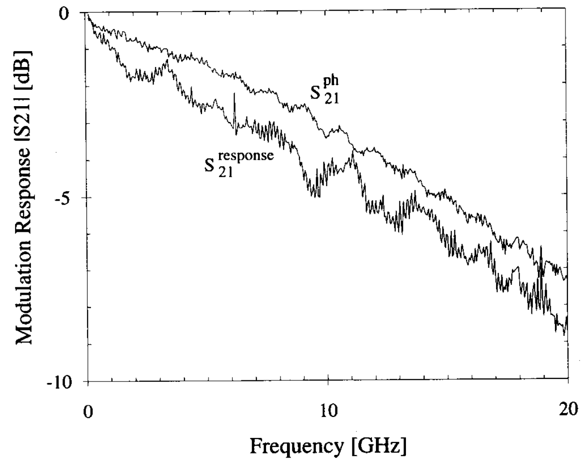

Fig. 3. Measured modulation response with and without the presented correction technique for an InGaAs–InP photodiode ($V_{bias} = -2$ V).

the photodetector is calculated using (12)–(15). In a second step, we measure E_{LF}, and together with S_{22}^{ph} we now use (8)–(10) to calculate the required error coefficients. Fig. 2 shows the magnitude of the three dominant error coefficients γ^{ph+p}, γ^p, and γ^{p+rx}, and the magnitude of the total error coefficient Γ. This result demonstrates that the attenuation of the microwave probe is the most important error, but the mismatch errors are not so small that they can be neglected. Fig. 3 reveals the measured modulation characteristic with and without the presented correction method at the reverse bias voltage V_{bias} of -2 V. As can be seen from Fig. 3, the new correction technique results in a smoother modulation response in comparison to the characteristic measured with the conventional response calibration implemented in the lightwave test set. As a consequence, the on-wafer determination of the -3 dB bandwidth (9 GHz) is more accurate using this new method. Especially the consideration of E_{LF}, the mismatch of the electrical receiver, gives an important improvement compared to the techniques described in [1]–[3].

IV. Conclusion

We presented an accurate de-embedding technique for the on-wafer lightwave measurement of optoelectronic detector devices. Mathematical expressions for the different error sources that exist in the characterization system were derived. The technique was applied to the modulation response measurement of an InGaAs–InP photodiode, and it showed more accurate results compared to previously reported measurement techniques. Especially the consideration of multiple reflections between the photodetector output, the wafer probe input, and the nonideal measurement system has proven to be a considerable improvement on the measurement accuracy.

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