Opto-Electronics Review

journal homepage: https://journals.pan.pl/opelre


# Direct characterisation of AM-to-PM phenomena in fast Si and InGaAs photodiodes

Grzegorz Budzyn[1*], Jędrzej Barański[1,2]

[1] Wroclaw University of Science and Technology, ul. Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland
[2] Lasertex Co. Sp. z o.o., ul. Swojczycka 26, 51-501 Wroclaw, Poland

**Article info**

*Article history:*
Received 10 Jun. 2024
Received in revised form 24 Sep. 2024
Accepted 07 Oct. 2024
Available on-line 05 Nov. 2024

*Keywords*:
photodetector;
phase;
noise;
laser;
nonlinearities.

**Abstract**

The direct measurement method of AM-to-PM phenomena in fast silicon and InGaAs photodiodes is described. The setup is simple, relatively inexpensive and allows fast and precise measurements not only in a laboratory environment. During sample tests, the authors have found that the influence of bias voltage on the phase shift of an optical signal conversion is significant. The reported effect together with the influence of modulation depth on phase shift (AM-to-PM conversion) has a negative impact on an optical signal reception especially in coherent applications. The authors show that, with our proposed setups, it is possible to find optimal bias voltage and optimal optical power in order to reduce electrical phase noise of the photodetector.

## 1. Introduction

Optical-to-electrical (OTE) conversion is a key part of many modern technologies such as optical frequency combs, optical spectroscopy, telecommunications networks, clock standards [1–3] along with time and frequency distribution networks [4–6], rangefinders [7], lidars and many more. With the increased availability of inexpensive high-frequency electronic and optoelectronic components, even more application areas are attracting market attention.

In each of these applications, it is important that the OTE conversion does not affect the end result, but real-world measurements show significant impact on signal delay during this conversion. Intensive research has shown that the delay in various types of photodiodes (PDs) depends on the intensity of the incoming optical signal or, in other words, on the average photocurrent flowing through the PD. These optimal points of the photocurrent are known as ‘null points’, for which the phase noise of such conversion is the lowest. For this reason, many attempts have been made to reduce this negative effect by finding ‘zero points’ or improving the design of PDs [8–11].

*Corresponding author at: grzegorz.budzyn@pwr.edu.pl

Unfortunately, many other factors affect this conversion. It was proven that the PD reverse polarization (bias) voltage also has a notable influence on the OTE conversion, along with the signal frequency at which the conversion is done. A very interesting explanation of these phenomena refers to changes in the carrier (electrons and holes) velocity in the p-i-n junction. The drift velocity is strongly dependent on the electric field in the depleted region of the junction, but photocurrent and bias voltage strongly affect this electric field. There are works that have attempted to investigate and explain this relation [12–16].

With the continuous improvement of highly integrated RF chipsets, test setups for electro-optical conversion in PDs are becoming cheaper and simpler as the use of advanced, complex, and expensive components such as pulsed lasers, EOM, or AOM modulators can now be replaced by cheaper and more integrated solutions. To prove this, the authors constructed two test circuits to accurately characterise the AM-to-PM effect in two types of PDs. They are based on high-performance I/Q demodulators from Texas Instruments, widely used in modern RF and telecommunications applications. These integrated devices work with signals up to 10 GHz, allowing the PDs to be characterised at a specific frequency. The idea is relatively simple, intuitive, and, importantly,

https://doi.org/10.24425/opelre.2024.152678
1896-3757/ Association of Polish Electrical Engineers (SEP) and Polish Academic of Sciences (PAS). Published by PAS

affordable for a commercial solution compared to other works such as Refs. 13 and 14. The proposed configurations allow PDs to be easily, quickly, and directly characterised over a useful input power range with a variation of various parameters such as signal frequency or diode polarization voltage.

Novel measurement results performed with proposed setups confirming the importance of OTE conversion in high-speed p-i-n silicon, as well as InGaAs PDs are presented. Based on obtained data, for better understanding of the observed phenomena, a SPICE model of the tested silicon PD was created. In the article, it is also discussed how to reduce the impact of AM-to-PM effects in high-frequency, phase-sensitive optoelectronic applications working either in visible or infrared range.

## 2. Silicon PD tests

The experimental setup for measuring the effects of bias voltage on phase and AM-to-PM in a free-space silicon PD is shown in Fig. 1. A Hamamatsu S5973 high-speed PD was adopted as the diode under test (DUT). A small photosensitive area of 0.12 mm$^2$ defines a high-frequency cut-off of 1 GHz at 3.3V bias. The authors decided to perform the test using a 1 mW 632.8 nm dual-mode HeNe laser tube, stabilized at modal equality. The tube outputs two perpendicularly polarized laser signals which can be easily beaten on a polarizer, forming a good quality AM signal. The optical interference of the two modes produces a beat frequency of 1084 MHz at a modulation depth of 90% delivering a very good testing signal. Laser light is then split by a non-polarized beam splitter (BS) into reference and measurement arms. The reference detector, powered at a constant bias, provides a fixed-phase signal to the RF path of the quadrature (I/Q) demodulator. The measurement signal passes through a tunable neutral density (ND) filter and a retroreflector (RR) back to the DUT.

The RR is mounted on a table with linear motion along the laser head and acts as delay line. This motion is necessary to reduce nonlinearities coming mainly from the RF electronics, as described in Ref. 17. In front of each PD (reference and DUT), there are linear polarizers set at the angle of 45 degrees. They are not shown for the clarity of presentation.

The idea of the setup is based on a measurement of phase difference between the reference and measurement signals. The reference signal is obtained from the reference detector REF. The I/Q demodulator TRF371109 mixes signals from the reference and measurement paths, providing a two-dimensional low-frequency signal to the microcontroller (MCU). Because the beat frequency of the chosen laser was about 1 GHz, thus between detectors and the mixer were used transimpedance amplifiers and impedance matched transmission lines. The phase difference is obtained by an arctan operation on the output signals of the I/Q demodulator. Before each measurement, the circuit is calibrated, i.e., the RR is moved along the beam by a distance equal to at least half the wavelength of the modulation frequency (in our case 14 cm), so that existing nonlinearities are compensated for by the MCU. The phase between the two arms was then measured. VBIAS voltage was changed, with the limits of the tested diode, i.e., from 0 V to −20 V. During tests of AM-to-PM effect, the variable ND filter was used to reduce the light intensity.

The advantage of the proposed test setup is its accuracy and sensitivity resulting from the fact that the I/Q demodulator works as a lock-in detector. Additionally, after calibration, the measurement procedure takes little time, thus a very precise measurement can be performed just by sweeping the bias voltage. The whole process can be automated with low effort making it possible to characterise batches of diodes during the production process.

A fine measurement step delivered interesting information about phase changes especially at low bias values. Observed phase shifts at different bias voltages and at four chosen settings of the ND filter are shown in Fig. 2. As can be seen, the dependence is nonlinear and is significant. At low bias voltage, the phase change increases with a visible threshold around 1 V. At about 1.9 V, a tipping point is observed. An increase of bias voltage above this point reverses the character of phase dependency. The phase delay can be easily converted to time delay by taking into account the period of the modulated signal. For example, a change of 10 degrees at 1084 MHz means a phase delay of 25.6 ps.

Although the diode is specified to work at a recommended bias of 3.3 V to achieve a 1 GHz bandwidth, it was found out that even at no bias voltage, the output signal amplitude was strong enough to deliver viable measurement results. This would mean that there is a possibility of using the S5973 PD in low noise, high-frequency application

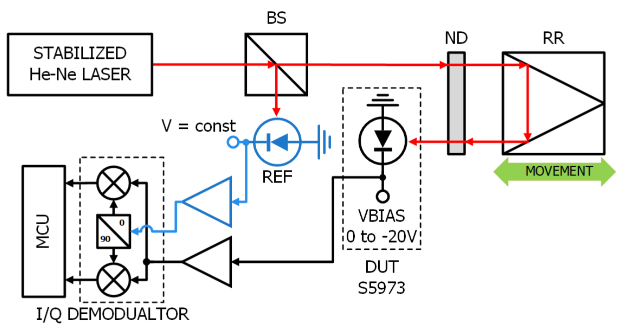


**Fig. 1.** Experimental setup. Optical paths are red and electrical paths are black or blue.

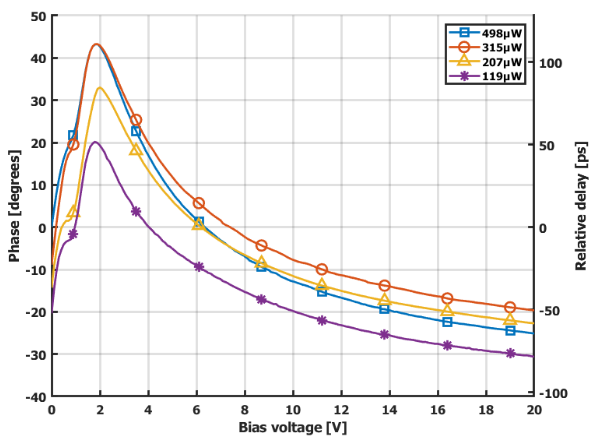


**Fig. 2.** Measurement results of bias to phase dependence for different powers of incident light. A measurement step of 0.1 V was used. For clarity of the graph, the tick points are reduced.

circuits where diode reverse polarization is avoided. Observed phase change character is qualitatively quite similar to characteristics of electrons and holes velocity in a p-i-n junction previously reported and theoretically described in the literature [13].

For further analysis, a widely adopted AM-to-PM conversion coefficient $\alpha$ was used. It is defined as:

$$\alpha = \frac{\Delta\varphi}{\Delta P / P} = \frac{\Delta\varphi}{\Delta I / I}, \tag{1}$$

where $P$ is the incident power, and $I$ is the photocurrent.

Because of the type of laser source used in the measurement setup, both denominators in (1) are constant at any input power. If the conversion coefficient for the measurement results is calculated (Fig. 3), then clear global minima can be seen around 1.9–2.0 V bias. The minima are narrow, but keeping the bias voltage for the tested diode in that range delivers the possibility of reducing phase noise coming from OTE conversion. A similar effect can be obtained at bias voltages close to the PD limits, i.e., between 18.0 V and 20.0 V. The disadvantage of this choice is the need for a high voltage usage which requires a noisy DC-DC step-up converter in battery powered devices or another voltage converter for main powered applications. The value of bias voltage recommended by the manufacturer turned out to be a poor choice for low phase noise applications.

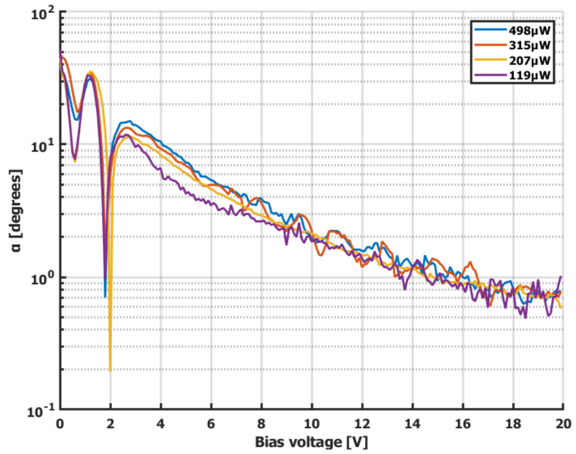


**Fig. 3.** AM-to-PM conversion coefficient change against bias voltage.

Another view on the conversion coefficient is shown in Fig. 4. There is a plotted dependence of α on the incident optical power with bias voltage as a parameter. The points of optimal value of conversion coefficient were registered to be within 310 W to 440 W of the input signal varying with the bias voltage except for 0 V bias. At this voltage, an optimal point was not registered. It can be predicted through extrapolate on that the optimal point at a very low bias should be at optical power above 500 W.

## 3. InGaAs PD tests

The system for testing silicon PDs has limitations regarding modulation frequency and output power due to the He-Ne laser used. Fortunately, in the case of the system

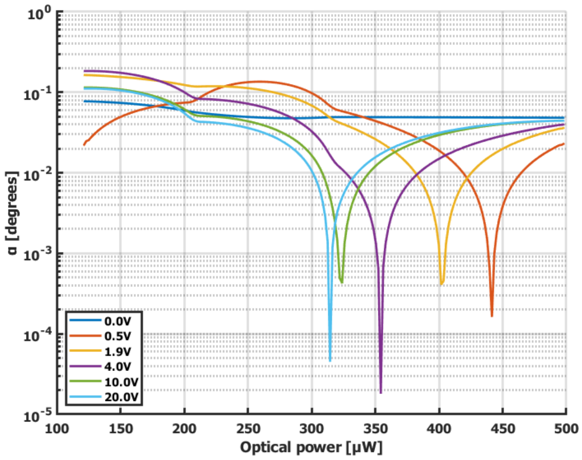


**Fig. 4.** AM-to-PM conversion coefficient change against optical signal strength.

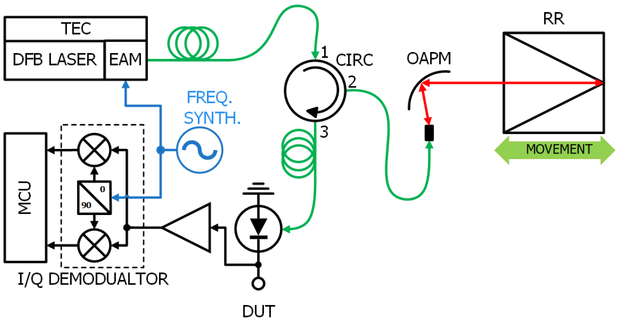


**Fig. 5.** Experimental setup for testing fibre-coupled PD for 1500 nm. Optical paths are red, fibre parts are green and electrical paths are black or blue. CIRC – fiber circulator, DUT – device under test, TEC – thermoelectric cooler, OAPM – off-axis parabolic mirror.

for testing InGaAs PDs (Fig. 5), it is much easier to find a laser source with an integrated optical amplitude modulator and a wavelength that matches the sensitivity region of such PDs. A DFB laser with an integrated electro-absorption modulator (EAM) and thermoelectric cooler (TEC) was chosen. The TEC allows the laser parameters to remain the same at any laser output power. The output power can vary from about 150 mW to 8 mW, but only about 30% of the output power is present at port 3 of the circulator. Frequency synthesis and I/Q demodulation are performed by the Texas Instruments LMX8410L in this setup. The IC can generate and mix RF frequencies from 4 GHz to 10 GHz. An RR is used for the same reason as in the first setup – signal delay is necessary to reduce nonlinearities in electronic circuits. The differences in circuit design [fiber circulator (CIRC), off-axis parabolic mirror (OAPM)] are due to the use of fibre-coupled components.

A Wooriro WPPTR100FNTCNC 10 Gbs receiver optical sub-assembly (ROSA) was used as DUT. The device contains a PIN InGaAs PD with an integrated transimpedance amplifier (TIA) and an LC/PC optical fibre connector, which is standard in telecommunication devices such as optical SFP+ transceivers. The RSSI output of the ROSA was adapted to measure the incident optical power to the PD rather than using optical power meter.

In order to prove the functionality of the setup, a series of measurements was performed. Unfortunately, for this kind of device, it is impossible to change the bias voltage of the PD, but this time, the authors focused on the incident optical power influence and input signal frequency on a phase shift of a fibre-coupled InGaAs PD electrical output. The DUT was tested at six different frequencies between 4 and 9 GHz with a 1 Hz step. The signal at 10 GHz had too low amplitude to trust this measurement. The incident optical power was swept linearly from 50 μW to 2400 μW with 8 μW steps. In Fig. 6, here are shown measurement results obtained with the developed setup in fully automatic mode – only calibration was done manually.

The obtained results show that at low input powers, there is a noticeable phase delay difference between signals of different frequencies. This fact is of the utmost importance, especially in coherent optical systems, but in general, phase shift is significant at a given input optical power range. This fact would be non-negligible, for example, in passive telecommunication networks.

Reduction of the AM-to-PM effect would be possible when choosing working points with the lowest conversion coefficient α defined by (1). As shown in Fig. 7, a few 'null points' for each signal frequency were observed. They are available at low input power and around 1.5 mW. Theoretically, the PD should saturate at 1500 μW, but the authors achieved a conversion up to 2400 μW of incident optical power. Plots are offset to 0 degrees at 1000 μW to show that increasing optical power can reduce phase shift at different frequencies. Changes of the phase are less rapid and similar at every frequency.

For the best effect, the optimal points should be found for every application, and the authors' setup seems to be the perfect tool for searching for those points.

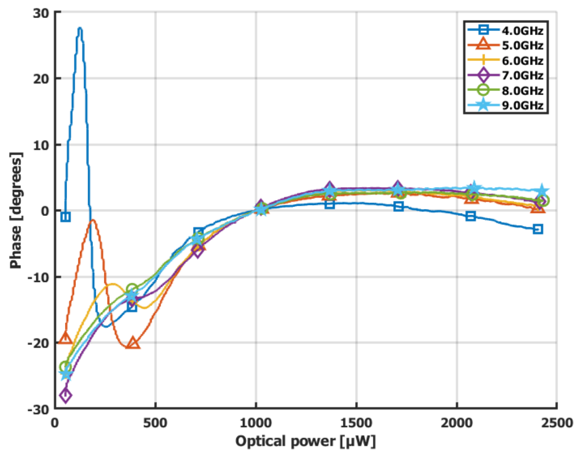


**Fig. 6.** Measurement results of bias to phase dependence for different powers of incident light for InGaAs PD. Plots are offset to 0 degrees at 1000 uW.

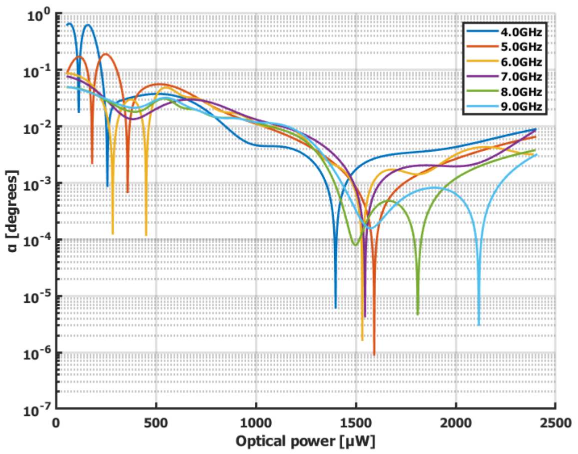


**Fig. 7.** AM-to-PM conversion coefficient change against optical signal strength for the InGaAs PD.

## 4. Results analysis

The proposed measurement setups provide accurate, high-resolution measurements that can be used to create a PD model that takes into account the dependence of signal delay during OTE conversion with respect to the bias voltage and intensity of the incoming optical signal.

In the literature, many different models of a p-i-n-type PD with varying degrees of complexity have been proposed. The standard approach is to model a PD with a SPICE electrical circuit composed of current source and passive RLC elements [18–20]. Another approach, which also takes into account the effect of a carrier transit-induced time delay and the effect of stored charge in high-power operation, uses an additional voltage-controlled current source (VCCS) in electrical circuit as transit-time element [21]. It is worth mentioning that values of resistance and capacitance in this model change as a function of incident light, as well as bias voltage. Numerous variations of this concept have been proposed for different designs of PDs [22, 23]. Attempts have also been made to add elements defined by a mathematical equation to the electrical circuit model, including nonlinear ones [24, 25].

In order to be able to reproduce the nonlinear phase delay of the signal during OTE conversion in PD, the authors have combined the discussed approaches and created their model of PD shown in Fig. 8. The model is SPICE-based and includes current source $I_1$ which acts as incident light (photocurrent), transit time and responsivity part modelled as $R_t$, $C_t$, and VCCS, inner diode modelled as a $C_j$, $R_j$, contact structure represented as $R_s$, $L_s$, and $C_p$. Resistor $R_L$ was used to model a PD load. Component values are described as mathematical equations with respect to the polarization voltage, especially, the junction capacitance $C_j$ as it is well defined in literature.

Components in the model were characterised to fit the data obtained at the highest input power of 498 μW in the S5973 silicon PD. A comparison of the simulation and the measurement is shown in Fig. 9. The shape at low bias voltage was mainly influenced by the transit time block delay, while the other part of the chart was modelled mainly with $C_j$ and $R_j$ components. Because the DUT was a highly integrated element, the influence of parasite components $R_s$, $L_s$, and $C_p$ was relatively low.

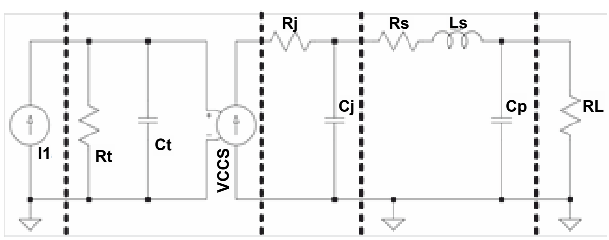


**Fig. 8**. Electrical model of p-i-n PD.

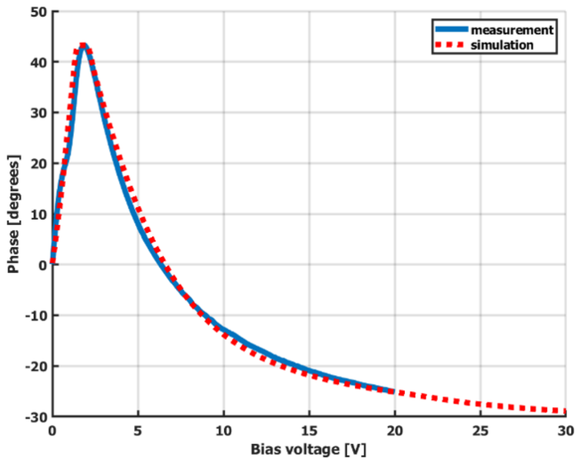


**Fig. 9.** Comparison of simulation results obtained in the proposed model against a real measurement for a silicon PD at maximum input power.

## 5. Conclusions

The authors have shown that using the proposed setups, the AM-to-PM effect in p-i-n silicon and InGaAs PD can be accurately characterised at different bias voltages, incident optical powers, and signal frequencies which allowed to find 'null points' in the tested PD. Setups based on I/Q demodulators and a delay line can be used to test PDs both in free space and fibre-coupled with a reference signal generated internally using a frequency synthesizer or externally using the beat frequency of a He-Ne laser. Both systems can perform high-speed measurements in an automated manner – characterisation of the InGaAs PD was performed almost fully autonomously. The presented systems are simple and more affordable compared to other solutions presented in literature. That gives the possibility to use such setups in commercial solutions.

Presented silicon p-i-n PD SPICE model almost perfectly reproduces real measurements of the S5973 PD, which is important for further analysis of that nonlinear phase change in other PDs.

## Conflict of Interest

The authors declare that no competing financial interest or personal relationship could have appeared to influence the work reported in this paper.

## References

[1] Hinkley, N. *et al*. An atomic clock with $10^{-18}$ instability. *Science* **341**, 1215–1218 (2013). https://doi.org/10.1126/science.1240420

[2] Fortier, T. M. *et al.* Generation of ultra stable microwaves via optical frequency division. *Nat. Photonics* **5**, 425–429 (2011). https://doi.org/10.1038/nphoton.2011.121

[3] Ma, L.-S. *et al*. Optical frequency synthesis and comparison with uncertainty at the $10^{-19}$ level. *Science* **303**, 1843–1845 (2004). https://doi.org/10.1126/science.1095092

[4] Predehl, K. *et al.* A 920-kilometer optical fiber link for frequency metrology at the 19th decimal place. *Science* **336**, 441–444 (2012). https://doi.org/10.1126/science.1218442

[5] Lisdat, C. *et al.* A clock network for geodesy and fundamental science. *Nat. Commun*. **7**, 12443 (2016). https://doi.org/10.1038/ncomms12443

[6] Eliyahu, D., Seidel, D. & Maleki, L. RF amplitude and phase-noise reduction of an optical link and an opto-electronic oscillator. *IEEE Trans. Microw. Theory Tech*. **56**, 449–456 (2008). https://doi.org/10.1109/TMTT.2007.914640

[7] Guillory, J., García-Márquez, J., Alexandre, C., Truong, D. & Wallerand. J.-P. Characterization and reduction of the amplitude-to-phase conversion effects in telemetry. *Meas. Sci. Technol.* **26**, 084006 (2015). https://doi.org/10.1088/0957-0233/26/8/084006

[8] Zang, J. *et al*. Reduction of amplitude-to-phase conversion in charge-compensated modified unitraveling carrier photodiodes. *J Light. Technol.* **36**, 5218–5223 (2018). https://doi.org/10.1109/JLT.2018.2871882

[9] Davila-Rodriguez, J. *et al*. Optimizing the linearity in high-speed photodiodes. *Opt. Express* **26**, 30532–30545 (2018). https://doi.org/10.1364/OE.26.030532

[10] Xie, X., Zang, J., Beling, A. & Campbell, J. Characterization of amplitude noise to phase noise conversion in charge-compensated modified unitravelling carrier photodiodes. *J. Light. Technol.* **35**, 1718–1724 (2017). https://doi.org/10.1109/JLT.2016.2641967

[11] Bouchand, R., Nicolodi, D., Xie, X., Alexandre, C. & Le Coq, Y. Accurate control of optoelectronic amplitude to phase noise conversion in photodetection of ultra-fast optical pulses. *Opt. Express* **25**, 12268–12281 (2017). https://doi.org/10.1364/OE.25.012268

[12] Matavulj, P. S., Golubović, D. S. & Radunović, J. B. Comparison of nonlinear and nonstationary response of conventional and resonant cavity enhanced *p-i-n* photodiode. *J. Appl. Phys.* **87**, 3086–3092 (2000). https://doi.org/10.1063/1.372304

[13] Sun, J., Xu, B., Sun, W., Zhu, S. & Zhu, N. The effect of bias and frequency on amplitude to phase conversion of photodiodes. *IEEE Photonics J.* **12**, 1–10 (2020). https://doi.org/10.1109/JPHOT.2020.3013836

[14] Kang, L. & Kolner, B. H. Characterization of AM-to-PM conversion in silicon p-i-n photodiodes. *IEEE Photon. Technol. Lett.* **31**, 1001–1004 (2019). https://doi.org/10.1109/LPT.2019.2914607

[15] Phung, D.-H., Merzougui, M., Alexandre, C. & Lintz, M. Phase measurement of a microwave optical modulation: characterisation and reduction of amplitude-to-phase conversion in 1.5 µm high bandwidth photodiodes. *J. Light. Technol.* **32**, 3759–3767 (2014). https://doi.org/10.1109/JLT.2014.2312457

[16] Hu, Y. *et al.* Computational study of amplitude-to-phase conversion in a modified unitraveling carrier photodetector. *IEEE Photonics J.* **9**, 1–11 (2017). https://doi.org/10.1109/JPHOT.2017.2682251

[17] Podżorny, T., Budzyń, G. & Rzepka, J. Linearization methods of laser interferometers for pico/nano positioning stages. *Optik* **124**, 6345–6348 (2013). https://doi.org/10.1016/j.ijleo.2013.05.054

[18] Natrella, M. *et al*. Accurate equivalent circuit model for millimetre-wave UTC photodiodes. *Opt. Express* **24**, 4698–4713 (2016). https://doi.org/10.1364/OE.24.004698

[19] Xu, Z. & Gao, J. Semi-analytical small signal parameter extraction method for PIN photodiode. *IET Optoelectron.* **11**, 103–107 (2017). https://doi.org/10.1049/iet-opt.2016.0051

[20] Kassem, A. & Darwazeh, I. Equivalent Circuit Model for Large-Area Photodiodes for VLC Systems. in *2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)* 467–472 (IEEE, 2022). https://doi.org/10.1109/CSNDSP54353.2022.9908056

[21] Wang, G. *et al*. A time-delay equivalent-circuit model of ultrafast p-i-n photodiodes. *IEEE Trans. Microw. Theory Tech.* **51**, 1227–1233 (2003). https://doi.org/10.1109/TMTT.2003.809642

[22] Song, Z. *et al.* Analysis of AM-to-PM conversion in MUTC photodiodes based on an equivalent circuit model. *Opt. Express* **29**, 33582–33591 (2021). https://doi.org/10.1364/OE.441677

[23] Wun, J.-M., Wang, Y.-W., Chen, Y.-H., Bowers, J. E. & Shi, J.-W. GaSb-Based p-i-n photodiodes with partially depleted absorbers for high-speed and high-power performance at 2.5-µm wavelength. *IEEE Trans. Electron Devices* **63**, 2796–2801 (2016). https://doi.org/10.1109/TED.2016.2561202

[24] Abdallah, Z., Rumeau, A., Fernandez, A., Cibiel, G. & Llopis, O. Nonlinear equivalent-circuit modeling of a fast photodiode. *IEEE Photonics Technol. Lett.* **26**, 1840–1842 (2014). https://doi.org/10.1109/LPT.2014.2337352

[25] Jou, J.-J. *et al.* Time-delay circuit model of high-speed p-i-n photodiodes. *IEEE Photonics Technol. Lett.* **14**, 525–527 (2002). https://doi.org/10.1109/68.992599