40-Gb/s PAM-4 Transmission over a 40 km Amplifier-less Link Using a sub-5V Ge APD

Jochem Verbist, Joris Lambrecht, Bart Moeneclaey, Joris Van Campenhout, Xin Yin, Johan Bauwelinck and Gunther Roelkens

Abstract—Avalanche photodetectors (APDs) integrated in a silicon platform have the potential to significantly improve the link budget of optical links compared to conventional p-i-n photodetectors, while only requiring CMOS-friendly biasing voltages. We demonstrate an optical receiver based on a 1310 nm <5 V Germanium APD and a low-power transimpedance amplifier that offers a 5-to-6 dB sensitivity improvement compared to operation in PIN-mode. Sub-FEC transmission using PAM-4 in an amplifier-less link over more than 42 km at 40 Gb/s and over more than 10 km at 50 Gb/s is shown with a commercial directly modulated laser as transmitter.

Index Terms—Avalanche Photodiode, PAM-4, Optical Receiver, Silicon Photonics

I. INTRODUCTION

As the bandwidth requirements keep surging, the access segment of passive optical networks (PONs) needs to transition to higher data rates beyond 10G. Due to the stringent power budget and cost factor, non-return-to-zero (NRZ) modulation is considered less suitable as it would require more premium high-bandwidth transceivers, while being less spectrally efficient and as such more susceptible to chromatic distortion. Several different bitrates and implementations are under investigation, such as 25G, 40G or 50G and mainly focused on 3-level duobinary and 4-level pulse-amplitude modulation (PAM-4) in order to leverage existing low-cost 25G-class components from the data center industry [1]–[3].

Avalanche photodiodes (APDs) have the ability to significantly increase the sensitivity of an optical receiver thanks to the avalanche gain [4], [5]. This property makes them especially valuable in power-limited optical networks such as PONs, where the extra sensitivity can be used to increase the split ratio, allowing one optical line terminal to serve more clients for the same transmit power. However, as it takes time to build up the avalanche, the bandwidth of such devices has typically been limited. Increasing the bitrate by combining PAM-4 modulation with a silicon-based APD, could be beneficial in terms of cost and power. This relaxes the bandwidth requirements on the electrical and optical components in the link, while still offering an improved sensitivity and power budget.

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J. Verbist, J. Lambrecht, B. Moeneclaey, X. Yin and J. Bauwelinck are with Ghent University - imec, IDLab, Department of Information Technology (e-mail: jochem.verbist@ugent.be)
J. Verbist and G. Roelkens are with Ghent University - imec, Photonics Research Group, Department of Information Technology.
J. Van Campenhout is with imec, Leuven, Belgium
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conventional III-V-based APDs as well as for most of the prior realizations of Ge waveguide APDs [6], [7]. However, [8] showed a Ge APD capable of 40 Gb/s NRZ at 3.4 V bias. Bit-error rate (BER) measurements were only performed for 10 Gb/s NRZ and indicated a relatively low estimated sensitivity of $<-16.5 \text{ dBm}$ at HD-FEC, at least 5 dB less than what the presented Ge APD in this paper achieved at twice the bitrate for NRZ [9].

In this letter, we demonstrate the first PAM-4 transmission at different rates (32, 40 and 50 Gb/s) with a waveguide-coupled Ge APD operated at a bias of less than 5 V. The device was fabricated on a 200 mm silicon-on-insulator platform and wirebonded to a linear, low-power TIA as shown in Fig.1. Transmission below the hard-decision forward-error coding limit (HD-FEC: BER of $3.8 \times 10^{-3}$) up to 40 Gb/s over more than 42 km in an amplifier-less link was obtained for an average received optical power above -14.4 dBm in APD-regime, a 6 dB sensitivity improvement compared to operation in PIN-regime. 50 Gb/s transmission required -11.3 dBm and was limited to 10 km due to the limited power budget.

II. DESIGN

The waveguide APD was designed in imec’s 200 mm silicon photonics platform. A vertical p-i-n structure is formed by implanting a 220 nm thick single-mode Si waveguide with phosphor ions (before Ge growth) and the planarized Ge layer with boron ions as shown in Fig.2a. To lower the bias voltage of the Ge APD a 185 nm thin Ge layer was used, resulting in a wafer-scale gain$\times$bandwidth product of 140 GHz at a bias voltage of 5 V. The primary responsivity was 0.3 A/W. Fig.2b shows the mean 3 dB bandwidth versus mean avalanche gain of the APD structure. Below a gain of 2 the mean bandwidth increases due to the widening of the depletion region in the Ge layer. Once the gain increases beyond 4 the bandwidth drops again due to the increased avalanche build-up time. The APD in this receiver had current-gain of 6.6 and an estimated bandwidth of $\sim$16 GHz. More details on the design, on-wafer characteristics, high-speed operation for NRZ data up to 28 Gb/s along with a discussion on how to improve the relatively low primary responsivity can be found in [9]. The Ge APD was wirebonded to a TIA to evaluate the large-signal multilevel performance. This electronic IC consists of a 2 channel TIA array fabricated in a 0.13 $\mu$m SiGe BiCMOS technology of which only one channel was used. The TIA was optimized in terms of power consumption and linearity to support multi-level modulation [10], [11]. The amplifier can deliver a 300 mVpp differential swing into a 50$\Omega$ load, has a bandwidth of more than 17 GHz and consumes less than 160 mW per TIA-channel. Both the APD and the TIA were placed in a cavity on a high-speed printed-circuit board to minimize the chip-to-pcb wirebond lengths.

III. EXPERIMENT SETUP

A commercial 25G-class directly modulated laser (DML) at 1310.2 nm was driven by an arbitrary waveform generator (AWG). Fig.3 shows the frequency response of the DML-transmitter, the APD-TIA receiver and the optical link consisting of both. The proposed receiver has a bandwidth of 14 to 15.4 GHz depending on the bias voltage. The laser has quite some peaking ($>4$ dB) between 10 and 20 GHz (Fig.3-a). As the focus of the experiment is on the optical receiver, the electrical signal from the AWG is used to flatten the frequency response from the transmitter up to 18 GHz, while connected back-to-back to a commercial high speed ($>34$ GHz) PIN-diode. The effect on the electrical and optical eyes is depicted in Fig.6. During bit-error-rate (BER) tests the AWG provided a PAM-4 modulated $2^{15} - 1$ long pseudo random bit stream (PRBS), which was amplified by a
50 GHz RF-amplifier to almost 2.5 Vpp to drive the DML. For all transmission experiments the DML was biased at 70 mA, resulting in an optical output power around 9 dBm. As we aim to demonstrate the feasibility of the proposed receiver in combination with a commercial transmitter for PON applications, no optical amplification was used in the link. Both DML and APD were operated at room temperature without any temperature control. Next, the light generated in the DML is sent through 10, 21 or 42 km standard single mode fiber (SSMF). Before entering the APD the power is controlled by a variable optical attenuator, after which the polarization is aligned to allow maximal power to be coupled into the waveguide structure through on-chip grating couplers (insertion loss \(\sim 6 \text{ dB}\)). Finally, the differential outputs of the TIA are stored by a 160 GSa/s real-time oscilloscope for offline BER-analysis. During this analysis a histogram of a fraction of the captured data was used to determine the optimal sampling time and the three corresponding decision thresholds to demodulate the received symbols into bits. No equalization or other offline post-processing was used. The memory depth of the oscilloscope limited the amount of received symbols to \(\sim 1\) million at 32 Gb/s, resulting in a measurable BER just below \(1 \times 10^{-6}\).

### IV. Results and Discussion

First, we determined the optimal bias voltage for the APD by minimizing the required optical power amplitude to obtain a BER below the hard-decision forward-error coding limit (HD-FEC) at 32 Gb/s. The optimal bias voltage was found to be -4.9 V, improving the receiver sensitivity 6 dB with respect to PIN-operation (at -1.2 V). The extinction ratio, measured between the minimal and maximal power levels of the four-level eye, was 4.8 dB. We investigated PAM-4 transmission at three different rates (i.e. 32 Gb/s, 40 Gb/s and 50 Gb/s) in PIN-mode and in APD operation, for which the BER-curves are presented in Fig.5. An example of the received eye diagrams at the different rates captured by a 50 GHz sampling oscilloscope can be found in Fig.6. At 32 Gb/s the HD-FEC limit required -15.3 dBm in APD mode for all transmissions up to 42 km with no noticeable penalty due to operation in O-band. In PIN-mode HD-FEC was reached at an average power of -9.3 dBm for all transmissions up to 21 km. At 42 km the power budget did not longer suffice to perform meaningful PIN-mode measurements due to a relatively low off-chip responsivity combined with the additional insertion loss of the VOA (\(-2 \text{ dB}\)) and fiber connectors of the SSMF, resulting in a maximal in-fiber power of around -6 dBm. At 40 Gb/s the average power had to be 1.1 dB higher to obtain error-free operation for APD (-14.4 dBm) as well as PIN operation (-8.4 dBm). Removing the VOA from the setup and replacing the relatively inefficient fiber grating couplers (-6 dB) with low-loss edge couplers (IL \(-1 \text{ dB}\)), would allow the proposed APD-based receiver to sustain a 1:32 split ratio at 40 Gb/s over more than 20 km without any optical amplification (for an unaltered DML output power of 9 dBm). Finally, at 50 Gb/s we can clearly see an error-floor appearing around \(1 \times 10^{-3}\) for both modes of operation. Nevertheless, we are still able to successfully transmit over 10 km of SSMF for an average received optical power above -11.3 dBm with avalanche gain and -6.2 dBm without avalanche gain, realizing a sensitivity improvement of 5.1 dB.

If we compare the 40 Gb/s and 50 Gb/s PAM-4 operation with the results obtained for NRZ modulation on the same receiver at equal baudrates (i.e. 20 Gb/s and 25 Gb/s)
as reported in [9], we can estimate the sensitivity penalty of doubling the bitrate through PAM-4 modulation. For 20 Gb/s a sensitivity (with respect to HD-FEC) of approximately -22 dBm of received optical power for a PRBS of $2^{31} - 1$ at an ER of 8.3 dB was obtained. For 25 Gb/s the sensitivity was approximately -21 dBm. For the PAM-4 transmissions discussed in this paper, we measured a B2B sensitivity of -14.4 dBm and -11.8 dBm for 40 and 50 Gb/s, respectively. The drop in sensitivity can attributed to two factors. Firstly, the extinction ratio of the DML, taken between min and max power level, in the PAM-4 experiments was limited to 4.8 dB. In the NRZ experiment a Mach-Zehnder modulator was used to modulate the light from an external cavity laser, leading to a significantly higher ER of 8.3 dB. Secondly, as PAM-4 modulation introduces four eye levels, the vertical eye opening of an ideal PAM-4 eye is reduced with a factor 3 (4.77 dB) compared to NRZ modulation for the same ER and average power. In practice, this penalty is even higher as the 4-level signal also introduces the need for linearity in order to minimize the compression of the outer eyes. Furthermore, it suffers from an increased amount of inter symbol interference in the presence of bandwidth limitations as the PAM-4 constellation has twice as many symbols as NRZ. Nevertheless, the receiver should still be able to sustain a loss budget of 30 dB for 40 Gb/s PAM-4 when implemented with a fiber-to-chip edge-coupler.

An integrated waveguide-APD allows to easily extend the functionality of the transceiver by adding additional blocks on the same photonic IC (wavelength division multiplexing filters, etc.), but it also introduces polarization sensitivity due to the TE-selective grating couplers. However, as this is a common concern when using integrated waveguide-based photonic circuits, several solutions exist. One option is to use 2D-grating couplers as reported in [12], which guide each polarization into a separate waveguide while simultaneously converting the TM-mode to a TE-mode. The waveguide with the TE-converted mode can then be fed to the back of the waveguide APD. Although this is probably the easiest solution, the 2D-grating coupler introduces again quite some insertion loss. A more efficient solution would be to use a low-loss spot-size converter which accepts both polarizations, together with a polarization splitter and rotator (e.g. in [13], [14]) to convert the TM into a TE-mode. Both waveguides can then again be connected to the front and the back of the waveguide Ge APD.

V. Conclusion

We have demonstrated a low-voltage SiGe waveguide-APD in combination with a linear BiCMOS TIA. Avalanche operation requires less than 5 V and provides up to 6 dB sensitivity improvement, enabling 40 Gb/s of PAM-4 transmission over more than 42 km or 50 Gb/s over more than 10 km. Moreover, at 40 Gb/s this receiver should allow to support a 1:32 split ratio up to 20 km without the need for any optical amplification, making it an attractive component for low-cost implementations of next-generation PON and EPON networks.

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