Uncooled High Speed Ge/Si Avalanche Photodiode for 50 Gbit/s-PON with 60 km Reach

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Abstract: A high-speed germanium on silicon APD is demonstrated for DSP-free 50G-PONs. Sensitivities of -24 dBm at 58.2 Gbit/s and -26.5 dBm at 50 Gbit/s over 60 km of fiber are experimentally obtained in real time with temperature from -40°C to 80°C.

1. Introduction

The bandwidth increase needed by new usages such as the metaverse or 6G pushes the standardization bodies to set up new standards providing bitrates up to 50 Gbit/s and 100 Gbit/s in the fixed access network domain. The cost and the complexity of the optoelectronic systems must remain low considering the numerous terminations. Regarding Passive Optical Networks (PONs), with the recent completion of the 50G-PON standard [1], efforts moved to the practical realization of such system and the selection of the optimal technologies. With intensity modulation and direct detection, the low sensitivity (i.e. -24 dBm in downstream) required at such high bitrate induces a challenging realization of low cost 50G-PON receivers. Particularly, digital signal processing (DSP) and optical amplification are becoming essential to reach very high optical budgets specifications (>29 dB). Some receiver technologies such as Semiconductor Optical Amplifier – Uni-Travelling Carrier (SOA-UTC) have been explored and very good performances have been reported [2-3] without the help of equalization techniques. But these components present some drawbacks such as the high electrical power consumption of the SOA and the polarization dependent gain which requires to manage the polarization of the received signal. Avalanche photodiode (APD) thanks to its high conversion gain can help to meet the sensitivity and high link budget requirement without the use of an SOA. However, conventional platforms for APD such as Indium Gallium Arsenide (InGaAs) and Indium Phosphide (InP) suffer from their relatively low bandwidth, typically 18 GHz [4]. Recent works show that Germanium on Silicon (Ge/Si) to higher bandwidth (up to 31 GHz in [5-6]), thanks to lower ionization rate and large gain-bandwidth product. This can help to reach bitrates over 50 Gbit/s in IM/DD system as in PONs. Moreover, Ge/Si APDs can be fabricated on commercial production Complementary Metal-Oxide Semiconductor (CMOS) foundry and then benefit of the existing knowledge and production systems of the silicon faculty.

In this paper, we assess in the context of 50G-PON, a Ge/Si APD Receiver Optical Sub-Assembly (ROSA) which presents a high conversion gain and a high bandwidth [5-6], and compare the results to 50G-PON specifications, without optical amplification nor DSP.

2. Experimental setup

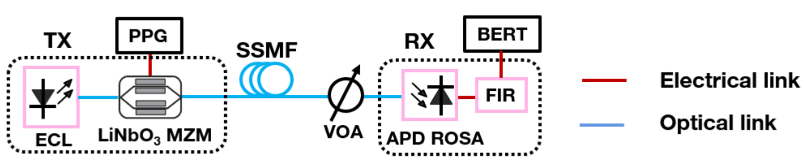

Fig. 1. Experimental setup

The experimental setup is described in Fig. 1. A Pulse Pattern Generator (PPG) is used to generate the electrical modulation signal at 50 Gbit/s and 58.2 Gbit/s with a Non-Return to Zero (NRZ) Pseudo Random Bit Sequence (PRBS) of length 2^{31}-1. The electrical modulation signal is amplified by a linear electrical driver and is then applied to a 40 GHz Electro-Optical Bandwidth (EO-BW) Mach-Zehnder Modulator (MZM). The MZM modulates an optical signal generated by an External Cavity Laser (ECL), leading to an Extinction Ratio (ER) equal to 8.8 dB (at 1310 nm). The signal propagates through 0, 20, 40 or 60 km of Standard Single Mode Fiber (SSMF) before reaching the APD after varying its input power with a Variable Optical Attenuator (VOA). The APD is packaged in a ROSA hosted on an Evaluation Board (EVB). The Germanium on Silicon APD is provided by SiFotonics Technologies. The bias of the APD (V_{APD}) is set at 19.8 V which correspond to its breakdown voltage minus 1.5 V (V_{BR}-1.5 V). The electrical signal is amplified by a Limiting Transimpedance Amplifier (LIA) integrated in the ROSA. The electrical bandwidth of the receiver (APD-ROSA+EVB) is enhanced with the help of an analog 6-taps finite impulse response (FIR) filter, with 7.5ps spacing. In our experiment, we measured the EO-BW at an input power of -15 dBm with and without a FIR filter. Finally, an error detector (ED) assesses the quality of the transmission measuring the bit error rate (BER).

3. APD-ROSA bandwidth and temperature performances

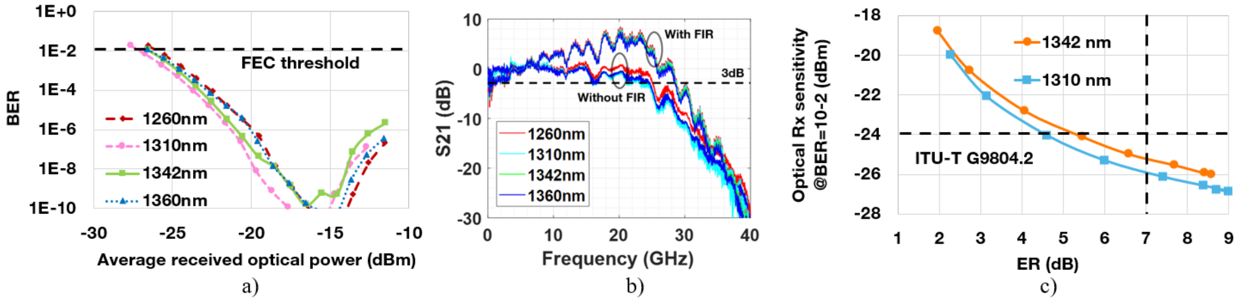

Fig. 2. a) BER versus average received optical power for 1260 nm, 1310 nm, 1342 nm and 1360 nm. b) Frequency response of the APD-ROSA with and without FIR filter. c) Receiver sensitivity at BER=10^{-2} as function of the extinction ratio for 1310 nm and 1342 nm.

On Fig. 2 a), we report the bit error rate (BER) measurement versus the average Received Optical Power (ROP) at different wavelengths with the APD at room temperature. We observe that the sensitivity at the FEC limit (BER=10^{-2}) stays in a range of 1dB for the whole wavelength range and reaches -26.5 dBm at 1310 nm. Fig. 2 also shows that the BER increases with the ROP, when the ROP exceeds -15 dBm. The saturation observed for ROP above -15 dBm, is probably due to the saturation of the LIA. Fig. 2 b) shows the normalized S21 measurements of the APD + EVB for 1260 nm, 1310 nm, 1342 nm and 1360 nm. Those wavelengths cover the range of the different operating wavelength options for the 50G-PON in upstream and downstream [1]. Fig. 2 b) also shows the electrical response of the APD-ROSA with the FIR compensation. The electrical response of the APD-ROSA remains the same for each of the wavelengths tested in this work without and with the FIR filter. As observed on Fig. 2 b), without FIR compensation, the 3 dB EO-BW of the ROSA is equal to 25 GHz at an input power of -15 dBm. With FIR filter compensation, the 3 dB EO-BW reaches 31 GHz owing to the resulting frequency boost around 20 GHz. The minimum ER required for a 50G-PON [1] emitter is 7 dB. Based on these results presented in Fig. 2 c), a receiver sensitivity below -24 dBm, as specified in the standard, is obtained if the ER is higher than 5.5 dB at 1342 nm and 4.7 dB at 1310 nm. Thus, this receiver can help on relaxing high constraints on producing emitters with high extinction ratio at 50 Gbit/s.

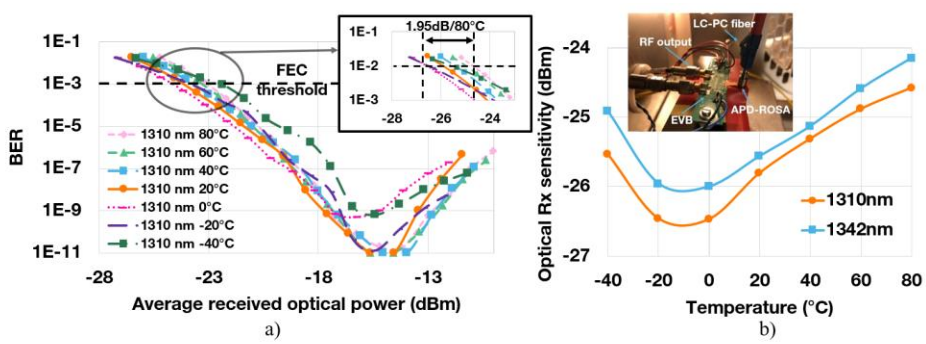

Fig. 3. (a)) BER as function of the average received optical power at 1310 nm for temperature from -40°C to 80°C. (b)) Receiver sensitivity at 1310 nm and 1342 nm for temperature from -40°C to 80°C

To check the compatibility with PON environment operation (-40°C, +65°C) [7], Fig. 3 presents the behavior of the uncooled APD ROSA placed in a climatic chamber to vary its temperature from -40°C to 80°C. It appears that the sensitivity (BER of 10^{-2}) of the APD+LIA+EVB system is degraded by 0.5 dB for every 20°C increase. At 60°C, near the maximum acceptable temperature in context of PON, the receiver sensitivity penalty is equal to 1.0 dB compared to the room temperature reference and remains below -24 dBm. Similar measurements are performed at 1342 nm, and results are summarized in Fig. 3 b). Thus, this uncooled APD can be operated at up to 80°C with a low sensitivity degradation allowing operation without controlling the temperature of the equipment or its environment. This makes this component compliant with operation in a 50G-PON context especially at client side.

4. Transmission performances

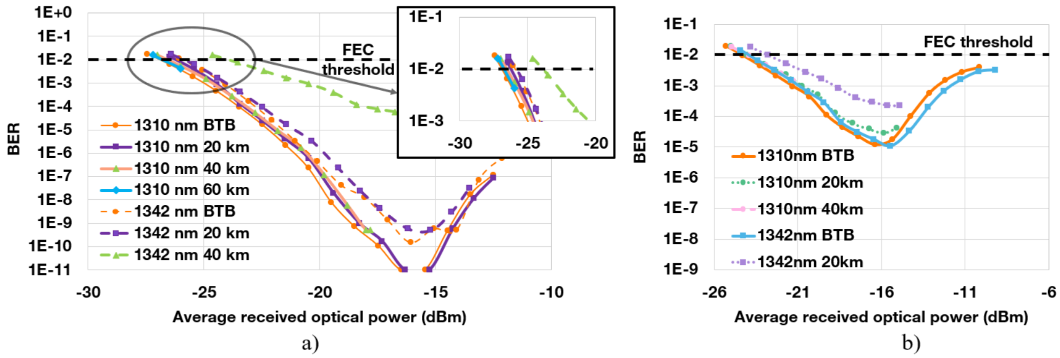

Fig. 4. (a) BER versus received optical power at 1310 nm and 1342 nm for 0, 20, 40 and 60 km. (b) BER versus received optical power at 1310 nm and 1342 nm in NRZ at 58.2 Gbit/s.

The capacity of the APD-ROSA to perform transmissions at 50 Gbit/s over 20 km of SSMF and beyond is assessed in this section at room temperature. The transmissions performances are presented on Fig. 4 a) at 1310 nm and at 1342nm for 0, 20, 40 and 60 km. The sensitivities at BER=10^{-2} for the four distances is stacked around -26.5 dBm at 1310 nm as the chromatic dispersion is negligible. This sensitivity is compliant with N1 and C+ budget class (29-32 dB) of the 50G-PON standard [1]. At a Tx wavelength of 1342 nm, 0 and 20 km results are very close with a measured sensitivity of -26.0 dBm. A chromatic dispersion penalty of 1.5 dB appears at 40 km, and no point can be measured at 60 km. For comparison, the required sensitivity of the receiver at such bitrate in the context of the 50G-PON is equal to -24.0 dBm in the downstream direction. No specification on the upstream receiver sensitivity at 50 Gbit/s is already edited. We have also assessed the capabilities of this APD-ROSA to support transmission beyond 50 Gbit/s. The electrical modulation signal is now set to NRZ at 58.2 Gbit/s, the maximum bitrate value allowed by our PPG. Fig. 4 b) shows the BER versus average received optical power at 1310 nm and 1342 nm in BTB, and after 20 km and 40 km of SSMF. We measured a sensitivity of -24.0 dBm at 58.2 Gbit/s without any optical amplifier and DSP-free.

5. Conclusion

We experimentally demonstrate that an avalanche photodiode fabricated in Germanium on Silicon is a strong candidate to enable high bitrate PON systems with low complexity signal processing and simple modulation format. Such devices can be produced in commercial CMOS foundry, allowing low cost per device and mass market production. To the best of our knowledge, this is the first time that a sensitivity of -24.0 dBm is experimentally demonstrated at 58.2 Gbit/s in intensity modulation and direct detection without optical amplification and DSP. We also showed the ability for the Ge/Si APD to meet the sensitivity requirements of 50G-PON on a -40 °C to +80 °C range without any cooling, and that the Ge/Si APD performances could relax the extinction ratio constraints on the transmitters.

7. Acknowledgments

We wish to thank Daqing Gu and SiFotonics for the APD and for their help on this work.

8. References

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