Beyond 100-Gb/s Direct-detection Transmission using an Optical Receiver Co-integrated with a 28-nm CMOS Gain-tunable Fully-differential TIA

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Abstract: We demonstrate up to 173.22-Gb/s direct-detection transmission using a balanced photodetector wire-bonded to a 28-nm CMOS fully-differential gain-tunable TIA. Both 100-Gb/s PAM4 and capacity-maximized adaptively-loaded DMT are studied for up to 2-km SSMF transmission.

1. Introduction

Recently, numerous efforts have been made to investigate low-cost, energy-efficient, and high-speed transceiver solutions for short-reach optical interconnects. Owing to their beneficial properties such as low-power consumption and compact size, the complementary metal-oxide-semiconductor (CMOS) and silicon photonics technologies as well as their combinations, are broadly considered as promising solutions. Transimpedance amplifiers (TIAs) play a dominant role in the optical receiver, since they largely determine the sensitivity, operation speed, linearity performance and power consumption of the receiver module [1-3]. Most of the high-speed TIA demonstrations to date have been based on the BiCMOS technology [1]. However, the inclusion of the TIA design in a standard CMOS process offers the advantages of lower cost and power consumption. Moreover, adopting the same standard CMOS process for the TIA in the optical receiver as for the subsequent digital signal processing (DSP) chips [4] eliminates the need for interconnection between the two, which can then also share the same ~1V power supply. A 53-Gbit/s optical receiver co-integrated with a 28-nm CMOS TIA was demonstrated in [2], which achieved an energy efficiency of 0.65 pJ/bit. In [3], a linear TIA in the 28-nm CMOS process was reported, and standalone electrical measurements and simulations indicated that it could potentially realize up to 112-Gb/s back-to-back (B2B) transmission.

In this work, we present an optical receiver where a balanced photodetector and a 28-nm gain-tunable fully-differential TIA are synergistically co-designed by jointly considering the circuit architecture, device packaging, power efficiency, operation speed, and footprint. With the fabricated optical receiver, both B2B and 2-km standard single-mode fiber (SSMF) transmission have been investigated using both 100-Gb/s Nyquist 4-ary pulse amplitude modulation (PAM4) and capacity-maximized adaptively-loaded discrete multitone (DMT) modulation. The results show that more than 2-dB receiver sensitivity can be gained by using the differential TIA structure. Using a ~1V power supply to the differential TIA, maximum data rates of 173.22-Gb/s and 139.86-Gb/s were achieved for the B2B and 2-km SSMF transmission respectively, with bit error rates (BERs) lower than 3.8×10^{-3}.

2. Receiver Implementation and Experimental Setup

Fig. 1(a) illustrates the block diagram of the proposed optical receiver. It is seen that a balanced photodetector is co-designed with a 28-nm CMOS fully-differential TIA to provide two differential outputs, thus avoiding the need for an extra step for single-to-differential conversion and offering enhanced linearity performance to the receiver. As shown in Fig. 1(a), the input optical signal was split into two identical parts by a 1×2 multimode interference (MMI) splitter. The resulting two optical signals were fed into two identical photoreactors, where the cathode node of photodiode1 (PD1) was tied to a bias voltage V_{bias1}=2V whereas the anode of the PD2 was tied to V_{bias2}=-1V. In this way, both direct and alternating current from the two PDs were generated complementarily. The subsequent fully-differential TIA was composed of three stages. The first stage was designed based on the standard shunt feedback resistor topology, where a NMOS transistor (M_{N_RF}) was connected in parallel with the feedback resistor (RF') to tune the transimpedance gain of the TIA. This could be simply achieved by adjusting the voltage supply (V_{ct}) to the NMOS transistors, as indicated in Fig. 1(a). We note that this gain-tunable function provides an effective way of balancing the gain and bandwidth of the optical receiver, which can be beneficial to practical short-reach systems of varying lengths. The second and third stages of the TIA were the CMOS-based limiting amplifier and the 50-ohm output buffer, respectively. Fig. 1(b) shows microscope views of the fabricated receiver and highlights the details of the wire-bonding between the balanced photodetector module and the TIA module. The TIA circuit was designed and fabricated based on the TSMC 28nm bulk-CMOS process whilst the balanced photodetector (TE_GSLPINCFCWT) was fabricated via the IMEC ISIPP50G platform. Note that the photodetector used in this work exhibited an ~33 GHz bandwidth whilst its responsivity was ~1A/W at 1550nm. Under a 1V power supply, the whole TIA circuit, including the output buffer, drew a current of ~51.4mA. Furthermore, simulations showed that the optical receiver has a transimpedance gain of around 52.5dBΩ whilst its 3-dB bandwidth is around 20GHz.

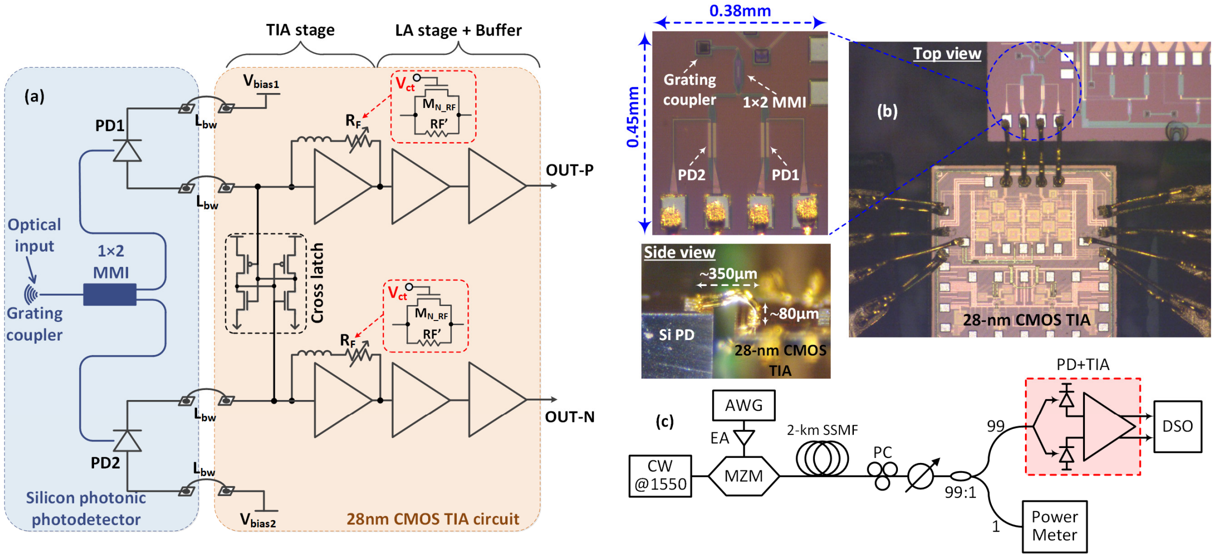

Fig. 1. (a) Block diagram of the proposed integrated optical receiver, (b) micro-scope view of the wire-bonded photodetector and TIA, and (c) experimental setup of the transmission system.

Fig. 1(c) shows the setup used to validate the performance of the fabricated optical receiver. A 1550-nm optical carrier with a power of 16 dBm was fed into a Mach-Zehnder modulator (MZM) for data modulation. The output of the MZM was directly launched to a 2-km length of SSMF. A polarization controller (PC) and an optical attenuator were used to adjust the polarization and received optical power (ROP) to the optical receiver, respectively. The resulting differential RF signals from the optical receiver were then captured by a digital storage oscilloscope (DSO) for further offline DSP. Note that in the single output case, only the 'OUT-P' output was used whilst in the differential output case, the two differential outputs were subtracted from one another in the offline DSP.

3. Experimental Results

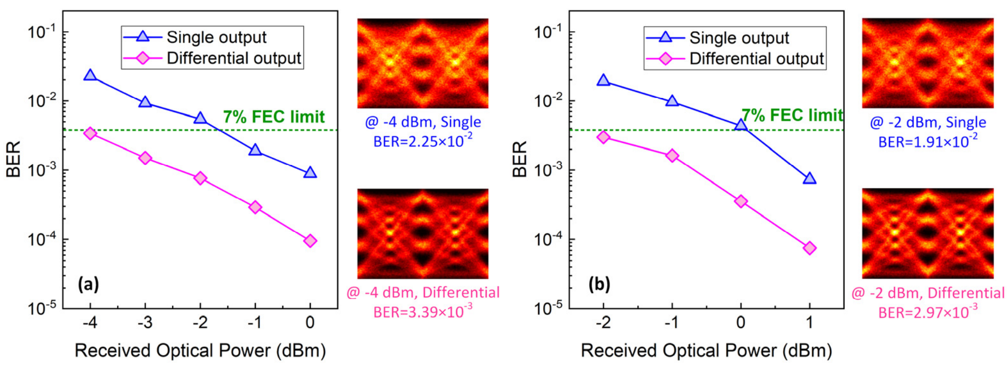

Fig. 2. BER versus ROP for 100-Gb/s PAM4 transmission: (a) B2B link, and (b) 2-km SSMF link.

We first investigated the performance of the fabricated optical receiver with a 100-Gb/s Nyquist PAM4 signal, while V_{ct} was fixed at 1.05 V. The BER comparisons of the signals received with the single or the differential output of the optical receiver in B2B and after a 2-km SSMF link are shown in Fig. 2 (a) and (b), respectively. For the B2B case, a ROP of ~-1.6 dBm was required when adopting OUT-P alone, in order to achieve a BER lower than 3.8×10^{-3}, i.e. the 7% FEC limit. When using the differential output, the required ROP was relaxed to ~-4 dBm. Note that the actual ROP to each PD was around 9-dB lower, due to ~6-dB coupling loss to the optical receiver and the 3-dB splitting loss in the 1×2 MMI. Compared to the B2B case, to accommodate transmission in the 2-km length of SSMF, the required ROPs were increased to 0.1 dBm and -2 dBm, respectively. For reference, the eye diagrams and the corresponding BERs at -4 dBm in the B2B link and at -2 dBm in the 2-km SSMF link are also reported in Fig. 2.

To evaluate the gain-tunable capability of the optical receiver, we further investigated the impact of the *Vct* setting on the transmission capacity in both B2B and the 2-km SSMF link using the adaptively-loaded DMT format. The ROPs of all cases were fixed to 4 dBm and the results are shown in Fig. 3. In principle, a decrease in *Vct* results in a higher TIA gain. However, this in turn results in a narrower electrical bandwidth of the integrated receiver. In the B2B case, the optimal *Vct* was around 1.1 V, at which the maximum capacity of the system can be improved from ~152.99 Gb/s to ~173.22 Gb/s by using the differential output of the TIA. At smaller *Vct* values, the capacity was mainly limited by the electrical bandwidth although the gain of the TIA was higher. In contrast, at higher *Vct* values, the reduced TIA gain was the main performance limiting factor. The SNR profile of the 173.22-Gb/s signal using the differential output in the B2B link with *Vct* being 1.1 V is shown in Fig. 3(e), in which subcarriers with up to 128QAM constellations were supported thanks to the excellent linearity of the fabricated optical receiver.

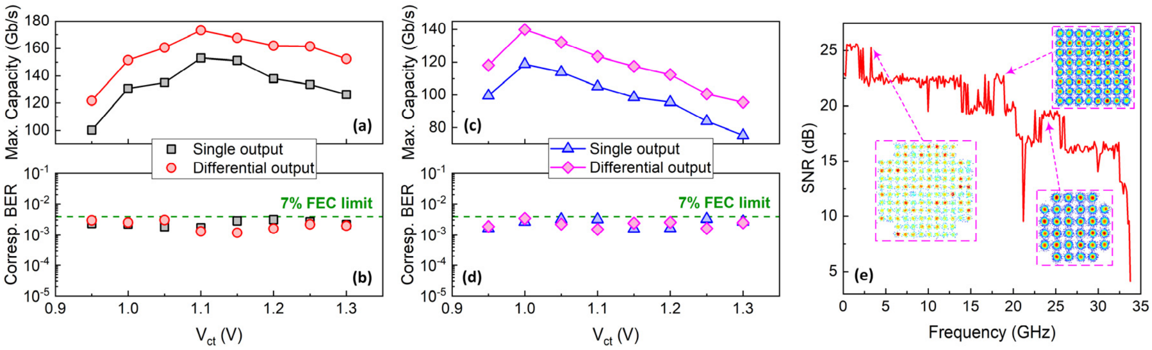

Fig. 3. Maximum capacity and the corresponding BER versus V_{ct} of the adaptively-loaded DMT transmission: (a)&(b) B2B link, (c)&(d) 2-km SSMF link; (e) SNR profile of the DMT transmission using the differential output in the B2B link with *Vct* being 1.1 V.

In comparison, the optimal *Vct* value decreased from 1.1 V to 1.0 V after transmission in the 2-km long SSMF, as shown in Fig. 3(c). This is because of the power fading effects imposed on the high-frequency subcarriers after this transmission length. Consequently, the usable electrical bandwidth of the overall system was further reduced. Therefore, a higher TIA gain rather than a higher receiver bandwidth was more beneficial to realize a higher data rate. With the optimal *Vct* of 1.0 V in the 2-km SSMF link, the achieved maximum capacities for the cases of single and differential output were 118.81 Gb/s and 139. 86 Gb/s, respectively. Note that the corresponding BERs of the adaptively-loaded DMT transmission were all below the 7% FEC limit, as shown in Fig. 3(b) and Fig. 3(d).

4. Conclusion

In this paper, we demonstrated 100-Gb/s PAM4 transmission and up to 173.22-Gb/s adaptively-loaded DMT transmission using a balanced photodetector wire-bonded to a 28-nm CMOS fully-differential gain-tunable TIA. We showed that the differential output of the optical receiver offers more than 2-dB receiver sensitivity improvement in the 100-Gb/s PAM4 transmission. Furthermore, we demonstrated the gain-tunable capability of the optical receiver through which the transimpedance gain and electrical bandwidth of the optical receiver can be balanced, showing promising potential for capacity maximization in short-reach interconnects over different lengths of fiber.

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5. References

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