Turning Zero-Bits of Parallel Interconnects into Optical Budget: Biasing APDs through Dumped Power

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Abstract: We prove the graceful migration to avalanche photodetection through reclaiming power that is available at transmitters. We demonstrate a sensitivity of -26 dBm for continuous/burst-mode 10 Gb/s/lane transmission, together with an extension to 32 data lanes.

I. Introduction

As interconnect bandwidths of switch cores surpass 10 Tb/s, the growth in information density remains unquestioned. Optical transceivers support this sustained growth in intra-datacenter link capacity through bandwidths of up to 100 GHz, ultra-small footprints and fJ/bit energy consumption [1]. These parallel optical interconnects typically operate in a simplistic point-to-point scheme with tight optical budgets. Optical switching could raise their efficiency while enabling novel datacenter architectures [2]; However, the advent of switching introduces burst-mode traffic, link-dependent optical budgets and extra loss due to signal distribution – quickly absorbing any unallocated budget available. A graceful migration to avalanche photodetection (APD) can be therefore beneficial [3], provided that the required changes at the electrical layer, such as high-voltage circuitry for biasing the APD elements, do not negatively impact the complexity and compactness of the transceivers. In this work, we collect and convert power that is naturally dropped at the transmitters to act as optical-layer supply for an APD bias, thus allowing for sensitivities of -26 dBm for 10 Gb/s/lane transmission without changes in the electrical link layer. We further investigate dynamic range and burst-mode limitations, and scale up to 32 lanes.

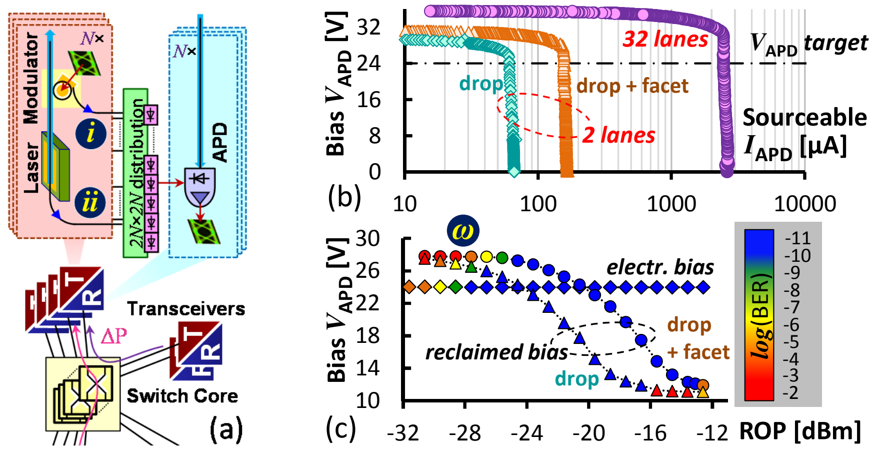

Fig. 1. (a) Parallel optical interconnect. (b) V-I characteristics for energy reclamation circuit and (c) resulting APD bias.

II. APD Bias Generation at the Optical Layer

As a method to extend the optical budget, we propose to reclaim unused optical power to generate an electrical supply for avalanche photodetection (Fig. 1a). The feed for this circuit stems from *(i)* optical zero bits that manifest themselves as power being dropped at the complementary output of an interferometric (eg, micro-ring or Mach-Zehnder) modulator of the local transmitter and *(ii)* the back-facet of the optical laser source of the same transmitter. We then distribute this optical feed P_{feed} equally to a serial stack of $2N$ photodiodes to generate a high no-load voltage V_{APD} >20V [4] with a corresponding short-circuit current given by $I_{SC} = R_{PIN}\, P_{feed} / L$, where R_{PIN} is the (worst) responsivity of the PIN diodes used in the stack and L is the loss of the $2N\times 2N$ distribution splitter. The latter can be space-efficiently realized using inverse design [5]. Since it can bundle the feed of N lanes, the aggregated feed per lane resembles a smaller contribution P_{feed}/N, typically a few dBm. Against this supply stands the demand in photocurrent due to the APD receivers at N lanes. It amounts to $I_{APD} = N\, M\, R_{APD}$ ROP, where ROP denotes the received optical power and M is the multiplication factor of the APD.

Our experimental setup (Fig. 2a) includes a two-lane 10-GHz DML transmitter (1554 nm, ER = 8.6 dB, see ε) and APD+TIA receivers. 50/50 splitters after the DML emulate the drop port of an interferometric modulator. Two more DMLs have been added to emulate the optical output at the back-facet of a laser source. This optical "waste" is then distributed by 4×4 and 16×16 star couplers to a stack of 64 PIN photodiodes to generate a shared bias V_{APD}. The TIAs are supplied by 3.3V. Cross-modulation effects for the APD responsivity due to the shared reclamation circuit are investigated by operating one of the lanes (λ_{BM}) in burst mode, using an optical switch (SWI) for carving out an idle period (β) at $f_S = 1$ kHz. Moreover, the power ratio ΔP between the burst- and continuous-mode lanes has been set through variable optical attenuators (VOA).

The energy scavenging characteristics (Fig. 1b) show that for a two-lane feed an APD current of up to 156 µA can be delivered at the optimum V_{APD} of 24V (△). For $R = 0.9$ A/W and $M = 10$ at $N = 2$, this would mean that this point is reached for a ROP of -20.6 dBm. For an elevanted number of $N = 32$ lanes, the sourceable current is 2.44 mA, at which the optimum V_{APD} is underrun for a ROP of -20.7 dBm. Figure 1c summarizes the receiver overload for a two-lane interconnect as function of the ROP. When the photocurrent cannot be longer sustained due to high ROP and V_{APD} drops accordingly, the BER – colorcoded in the marker symbol – increases.

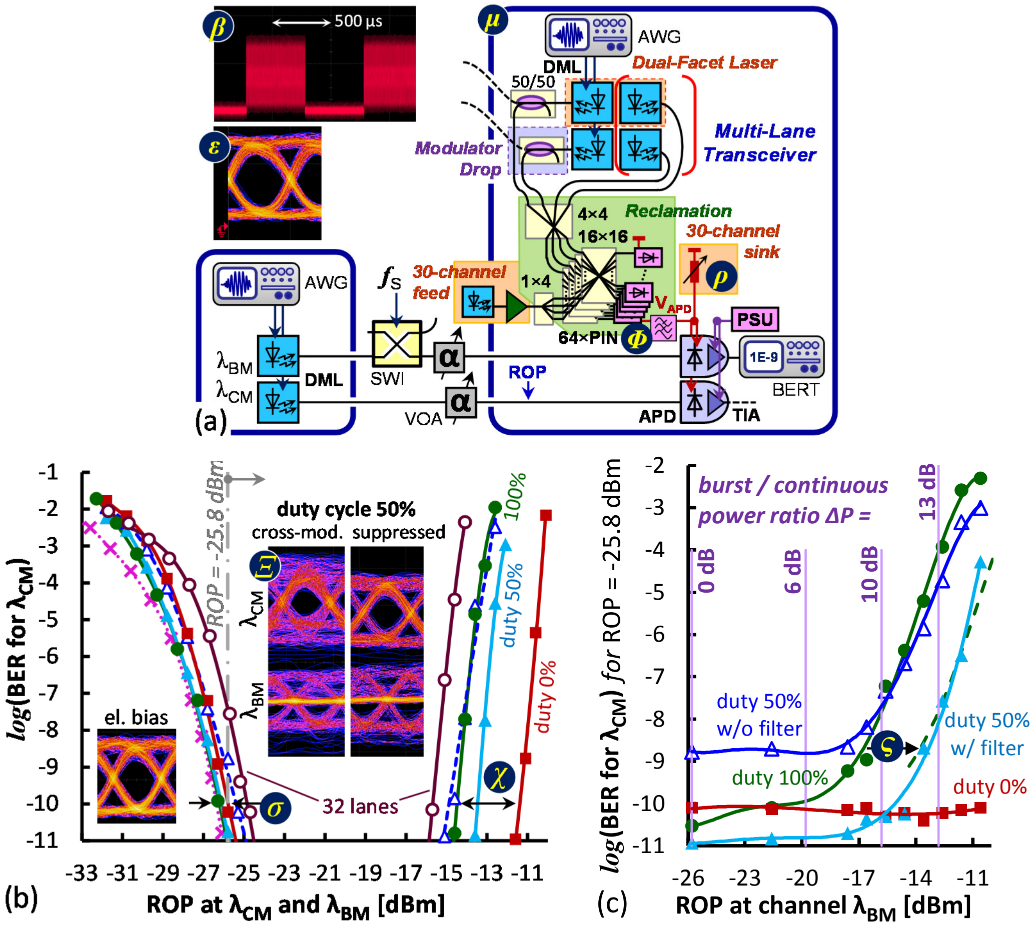

Fig. 2. (a) Experimental setup and BER for (b) two lanes with same ROP but variable burst-mode duty cycle, as well as for (c) an imbalanced power ratio.

III. Data Transmission in Parallel Interconnect

Figure 2b presents the BER for 10 Gb/s transmission for ΔP = 0. We take the APD, electrically biased at the optimum V_{APD} of 24V, as a reference (×). It yields a sensitivity of -26.4 dBm at a BER of 10^{-10}. Next, we investigated the case of optically biased APDs. For the extreme case where the switched lane features a burst-mode duty cycle of 100% (●), meaning that both lanes are operated in continuous-mode, a similar BER is found. For a duty cycle of 0% (■), meaning that no signal is received although an optical feed is provided to the reclamation circuit, an excess APD bias is obtained since a smaller photocurrent is drawn from the bias rail. The deviation from the optimal value of 24V leads to a 0.4 dB penalty (σ).

Towards higher ROP we see a BER increase attributed to the limit in photocurrent sourceable by the reclamation circuit. We surpass the BER level of 10^{-10} at a ROP of -11.4 and -14.5 dBm for a duty cycle of 0% (■) and 100% (●) at the burst-mode lane, respectively. The difference χ of 3.1 dB is explained by the extra power feed when no signal is received at the burst lane. This acts beneficially as it permits to sink a higher photocurrent associated to the higher ROP. In the worst case, the dynamic range is 11.7 dB, while the sensitivity and thus the optical budget can be boosted with respect to a PIN photoreceiver. This finite dynamic range is still larger than the typical point-to-point interconnect budget of 6 dB [6].

When choosing an intermediate duty cycle of 50% (△), we do not observe a BER performance between these two extreme cases but rather a worst-case situation among these, tantamount to an excess bias at low ROP and an early overload. However, this BER degradation derives from cross-responsivity modulation due to the burst-mode traffic at the second lane, as it is evidenced from the eye diagram (Ξ). This effect is analyzed in Fig. 2c, which shows the BER of the continuous-mode lane at a ROP of -25.8 dBm against the power difference ΔP between burst- and continuous-mode lane, for which ΔP > 0 dB denotes a stronger burst-mode signal. We see patterning due to a modulated APD responsivity with increased ΔP, resulting in a strong BER degradation (△). For comparison, Fig. 2c shows a low BER of 10^{-10} for the continuous-mode lane when the burst-mode signal is disconnected (■). We then suppressed bias artifacts due to cross-responsivity modulation by means of burst frequency suppression circuit (Φ in Fig. 2a), leading to a clear reduction in BER penalty (▲). The BER increase for higher ΔP is attributed to the overload of the bias reclamation circuit for high aggregated optical input power, as evidenced by the BER for the continuous-mode lane with a duty cycle of 100% for the burst-mode lane (●): the same slope in BER decrease is noticed, however, at a 3-dB offset (ς) that accounts for the 50% burst-mode duty cycle at λ_{BM}. This means that cross-responsivity modulation does not introduce a significant BER penalty up to ΔP = 12 dB. The improvement in BER at ΔP = 0 (▲) with respect to the disconnected burst-mode lane (■) is again explained by the sub-optimal excess APD bias for the latter. This result for cross-responsivity suppression under burst-mode co-existence is reported in Fig. 2b, where the continuous-mode lane now features an improved BER (▲).

Finally, we have investigated the BER for 32 lanes by emulating 30 more lanes at the transmitter side through an EDFA-boosted optical signal. At the receiver side, we emulated 30 more APD receivers through a load resistor (ρ in Fig. 2a) adjusted to sink the respective photocurrent of these receivers for the actually set ROP and multiplication factor $M = M(V_{APD})$. Figure 2b shows that the BER for 32 lanes (○) resembles a widely similar performance as that for two lanes. Given the potentially small footprint of the energy reclamation circuit by virtue of compact photodiodes and an inversely designed star coupler, the proposed circuit can be seamlessly integrated with the arrayed transceiver arrangement.

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IV. References

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