200G IM/DD Time-and-Polarization-Division-Multiplexed PON with >29dB Power Budget Using Boosted EML and APDs

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Abstract: We experimentally show feasibility of downstream 200 Gbit/s IM/DD TPDM PON system with >4 dB margin to 29 dB optical power budget based on two 100 Gbit/s polarization channels in a single wavelength window. The system uses SBS suppression to mitigate nonlinear fiber loss and duoternary modulation to overcome bandwidth limitation. © 2024 The Author(s)

1. Introduction

The ITU-T Q2 forum is currently aiming to identify suitable technology options for next-generation passive optical network (PON) systems operating at peak rates beyond 50 Gbit/s (50G) under the framework of Very High Speed PON (G.sup.VHSP). 100G and faster systems are in scope to enable throughputs required by new services and use cases, such as cost-efficient optical fronthaul transport, critical infrastructure or industrial use, and their combination with conventional use cases through access network slicing [1].

200G PON has been experimentally realized using both coherent and IM/DD technologies. However, the former approach, considering the current state of coherent technology, constitutes a significant step in complexity, as well as cost [2]. As a result, the incumbent IM/DD TDM technology is preferred if it can meet performance targets. In [3], 200 Gbit/s PON over 29 dB optical budget was realized using single-wavelength 4-level pulse amplitude modulation (PAM-4) at 100 GBd, distributed Raman amplification and SOA-filter-PIN receiver (Rx). More recently, two wavelength channels of 100 Gbit/s PAM-4 and SOA-filter-PIN Rxs were used to reach 200G in [4]. Another method to double the throughput is polarization multiplexing of two orthogonal channels coupled with active optical polarization tracking at Rx to allow for IM/DD time-and-polarization-division-multiplexed (TPDM) PON. TPDM is an attractive alternative to wavelength multiplexing in the already congested O-band, enabling straightforward duplication of transceiver branches while operating in the same wavelength window. A similar approach has been previously studied for long haul systems [5], and in the context of 800G for datacenters [6], or for a DSP-lite coherent [7].

In this paper we demonstrate feasibility of a 200G IM/DD PON system realized by polarization multiplexing of two 100 Gbit/s PAM-3 channels (orthogonal polarization tributaries) in the same wavelength window. At the transmitter (Tx) side, we employ a praseodymium-doped fiber amplifier (PDFA) to obtain high launch power to satisfy optical power budget requirements of future PON. Our results indicate that state-of-the-art electroabsorption-modulated lasers (EMLs) [8] or EML-SOAs [4] could potentially be used instead of PDFA to provide the necessary launch power. At the Rx side, we use a polarization controller and a polarization beam splitter to separate the two polarization channels, which are detected with two individual Rx branches equipped with avalanche photodetectors (APDs) with transimpedance amplifiers (TIAs). The resulting signals are decoded as duoternary [9] to overcome component bandwidth limitations and suppress equalization-enhanced noise [14]. The investigated system maintains typical PON complexity asymmetry, enabling sharing of the booster amplifier across all PON users.

2. Time-and-Polarization-Multiplexed Passive Optical Network (TPDM-PON)

2.1 Transmitter and Receiver: Dual Polarization Diversity with IM/DD

Fig. 1 shows Tx an Rx concepts that could be used in a TPDM-PON. Preferably, 200G OLT is integrated (Tx A), or, in a fashion similar to NG-PON2, could employ 100G OLTs in tandem with an external passive or active polarization mux (Tx B). The Rx side can use an integrated 200G dual-polarization (DP) ONU with an active polarization tracker and two Rx branches (Rx I), a 100G single-polarization (SP) ONU with an active polarization tracker and one Rx branch (Rx II), or a tandem of 100G ONUs with an external polarization demux (Rx III). Different than a wavelength approach, which forbids spectral overlap between two channels, a DP system relaxes the wavelength requirement, allowing for spectral overlap of both polarization channels. Demultiplexing at the Rx can be performed with a single polarization demux if wavelengths of two channels are within a few nanometers. As shown in Fig. 1, polarization

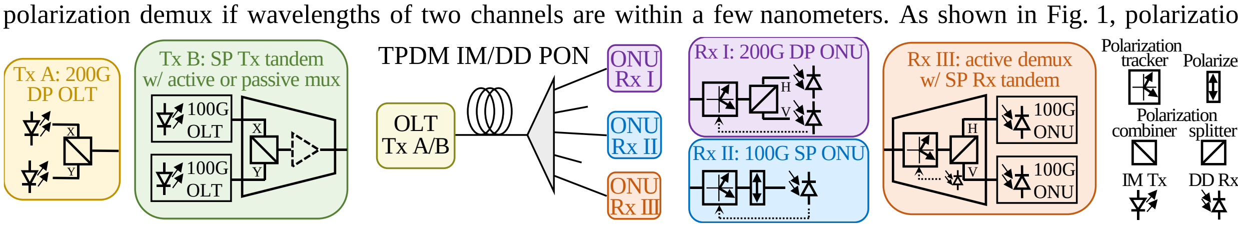

Fig. 1. Time-and-polarization-division-multiplexed (TPDM) PON with various transmitter and receiver options.

multiplexing also allows for delivery of varying service levels: 200G and 100G ONUs can be reconfigured simply and inherently, as opposed to the dual wavelength case [4], where switching between wavelength channels cannot be easily achieved by thermal filter tuning due to their broad separation.

2.2. High Launch Power: Stimulated Brillouin Scattering and Optical Power Budget Under Nonlinear Fiber Loss

In order to meet the optical power budget matching deployed PONs and compensate for receiver sensitivity loss as the bitrate goes up, high power needs to be launched from the Tx. In IM/DD PON, where high-power optical carrier is not suppressed, unlike in e.g., carrier-suppressed optical duobinary [10], stimulated Brillouin scattering (SBS) [11] will occur in the feeder fiber leading to saturation of the fiber output power effectively capping the achievable optical power budget, cf. Fig. 2(a,b). In this work we apply SBS suppression by amplitude dithering the bias current of the semiconductor laser source operating in the linear regime, which broadens the linewidth due to intrinsic amplitude-to-phase coupling in semiconductor lasers [12] and suppresses stimulated Brillouin scattering in the fiber. Using this technique, we fully mitigate 4.2 dB nonlinear fiber loss which otherwise is present at 15 dBm launch power, see Fig. 2(b).

2.3. 100 Gbit/s Channel: Precoded PAM-3 and Duoternary Equalization with Modulo-based Decoder

In the literature, 100 Gbit/s PON has been realized by using PAM-4, which helps to reduce the required analog bandwidth compared to PAM-2. Nevertheless, PAM-4 imposes an increased requirement on linearity, preventing the Tx and Rx from operating in the large-signal nonlinear regime, which provides gain to PAM-2 signal. As a result, PAM-4 systems typically exhibit a reduced outer optical modulation amplitude (OMA) compared to PAM-2 and thus higher sensitivity penalty. PAM-3 modulation, on the other hand, offers the following two advantages: (i) moderate bandwidth requirement (for 100 Gbit/s the spectral support is 33.3 GHz, compatible with analog bandwidth of state-of-the-art EMLs), (ii) better tolerance to nonlinearity than PAM-4, enabling maximization of OMA at the Tx, as well as higher tolerance to multipath interference (MPI). To overcome the bandwidth limitation at the Rx, a partial-response equalization and detection is employed. The Rx equalizer targets a duoternary output signal (class I partial-response (1+D)-encoded PAM-3 signal [9,13]), which has a 3 dB bandwidth of only 16.7 GHz, in-line with bandwidths of APDs developed for 50G PON (as the receiver bandwidth implied by 50G PON is 18.75 GHz). Moreover, detection of signal as duoternary can help to reduce the equalization-enhanced noise. Finally, by employing precoding at the transmitter, decoding of duoternary signal can be performed using only modulo operation [14]. As a result, 67.2 GBd PAM-3 (100.8 Gbit/s) transmission and duoternary reception can be realized with 25G-class components nominally designed for 50 GBd PAM-2.

3. Experimental Setup and Results

The experimental setup is depicted in Fig. 2(c). The optical carrier originates from a distributed feedback laser section of an integrated EML emitting at 1307.2 nm. The DC laser bias current is 60 mA and is modulated with a 10 kHz dither sine tone with 4.2% modulation depth. 67.2 GBd PAM-3 based on time-domain two-dimensional square QAM-8 constellation is precoded using a 1/(1+D) filter followed by a modulo operation to limit the output amplitude to 3 levels. The electrical signal is pre-emphasized to maximize OMA and loaded to a 120 GSa/s digital-to-analog converter. The electrical signal is amplified by an amplifier driving the electro-absorption section of the EML. The resulting modulated optical signal is subsequently boosted by a PDFA to 20.5 dBm. Next, the signal enters a polarization multiplexing (PolMux) emulation stage having 2.5 dB insertion loss (in actual system this loss would be reduced to 0.5 dB when replaced with a polarization combiner only), where an SP input signal is combined with its copy delayed by ~10 ns and rotated to the orthogonal polarization. The DP signal is sent to the receiver, either back-to-back or over a 20 km standard single-mode fiber (SSMF). For backscatter measurements, a circulator is connected to measure the backreflected power. In front of the receiver, a variable optical attenuator is used such that the receiver sensitivity can be swept. At the receiver, the signal passes through a polarization controller (PC) (assumed loss for on-chip adaptive PC implementation is 1.5 dB) and a polarization beam splitter (PBS) (0.5 dB). A diplexer is not present, but for the subsequent calculation of the optical budget, 0.5 dB loss is assumed. The PC can be iteratively optimized based on receiver-side monitoring of an amplitude marker tone added per-polarization at the transmitter, for which purpose the residual SBS dither tone can be reused. After the PBS, two polarization channels are split and provided to two receiver branches, horizontal (H) and vertical (V), each equipped with an independent APD-TIA. The electrical signals from the photoreceivers are simultaneously digitized using a 33 GHz oscilloscope sampling at 80 GSa/s and independently processed offline. The digital signal processing chain performs clock recovery to 2 samples per symbol,

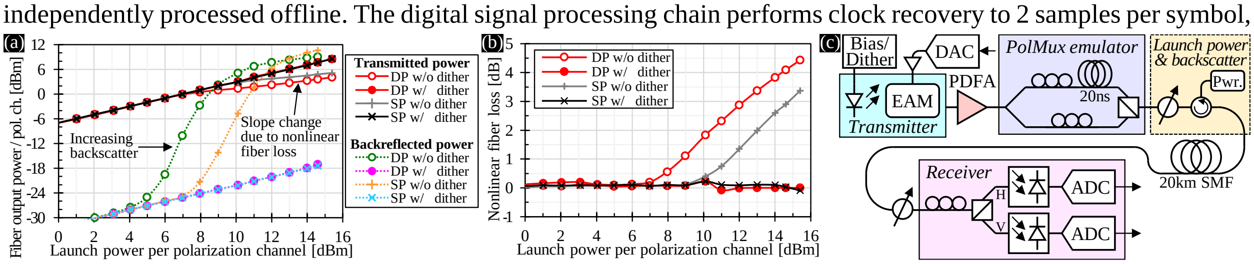

Fig. 2. (a) Transmitted and backreflected fiber power per polarization channel for SP and DP signals without and with SBS suppression dither. (b) Nonlinear fiber loss as a function of launch power for SP and DP signals without and with SBS suppression dither. (c) Schematic of the experimental setup.

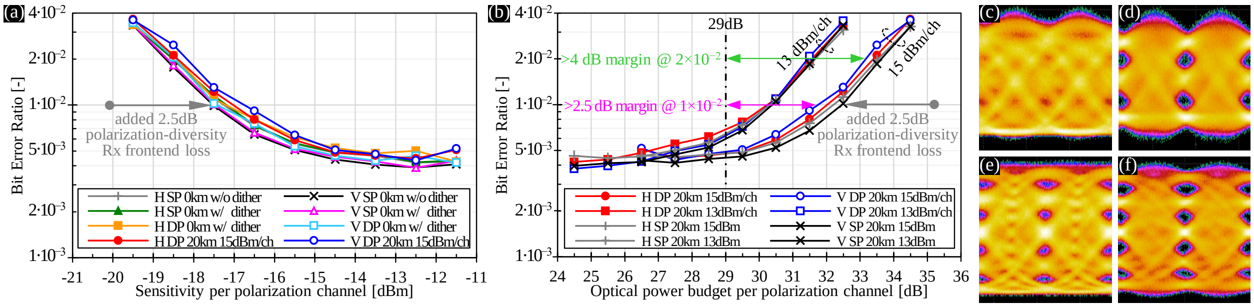

Fig. 3. (a) Receiver sensitivity per polarization channel, and (b) optical power budget per polarization channel, both after accounting for 2.5 dB polarization-diversity frontend loss. H,V – receiver branches. (c-f) Eye diagrams acquire on an equivalent-time oscilloscope.

equalization using a linear feedforward equalizer targeting 5-level duoternary signal, symbol boundary alignment and decision in two-dimensions, modulo decoding, symbol-to-bit demapping and error counting. Bit error ratio (BER) is counted on the last 65,536 bits of the acquired oscilloscope trace, and each BER value is derived as a mean of 50 traces. Eye diagrams captured with an equivalent-time oscilloscope at Tx are shown in Fig. 3: (c) Tx eye (partly closed due to intentionally induced OMA-bandwidth tradeoff to improve average power (AVP) sensitivity); (d) Tx eye equalized to PAM-3; (e) Tx eye after 22 GHz fourth-order Bessel filter, emulating APD-TIA bandwidth used in the experiment; (f) eye in (e) equalized to duoternary.

Fig. 2(a) shows transmitted and backreflected optical power for SP and DP signals when SBS dither is enabled or disabled. Fig. 2(b) shows the nonlinear fiber loss calculated from Fig. 2(a). One can see that without SBS suppression, a nonlinear fiber loss of 4.2 dB is incurred. This accounts only for fiber loss and does not consider further degradation of sensitivity due to counterpropagating high-power backscatter.

Fig. 3(a) shows the sensitivity at receiver input for various cases, where an extra 2.5 dB was added to account for polarization-diversity Rx frontend loss (0.5 dB diplexer + 1.5 dB adaptive PC + 0.5 dB PBS). Curves for H and V branches are shown, between which a difference of ~0.5dB is observed. SP performance is measured by setting the PC such that the signal is equally split at the PBS across H and V branch. No performance degradation is observed at 0 km between the case without SBS dither tone (H=+,V=×) and with (▲,△). A small (~0.3 dB) penalty is observed for DP signal back-to-back (■,□), which we attribute to inaccuracies in polarization alignment and finite polarization extinction ratio. The same signal after 20 km of SSMF (●,○) exhibits only 0.5 dB performance loss due to operation close to zero-dispersion wavelength (ZDW). Fig. 3(b) shows the optical power budget per polarization, for two different launch powers per polarization: 15 dBm and 13 dBm. All measurements are performed with SBS dither. SP performance at 13 dBm (dashed +,×) coincides closely with DP performance (■,□). At 15 dBm, DP performance (●,○) is 0.5 dB worse than SP performance (solid +,×). The margin to 29 dB link loss budget is more than 4 dB when evaluated at BER threshold of 2×10^{-2} or more than 2.5 dB at BER 1×10^{-2}. This margin can be spent on unaccounted penalties, such as chromatic dispersion (not present and not evaluated here due to near-ZDW operating wavelength), imperfect polarization demultiplexing, excess components loss, or higher PON budget class. At 13 dBm launch power, the unallocated system margin to 29 dB link loss budget decreases to ~2.5 dB at BER 2×10^{-2}. Considering that state-of-the-art EML(-SOAs) are able to launch at least 13 dBm per channel, and taking into account additional polarization beam combiner (0.5 dB) and diplexer (0.5 dB) losses at Tx, 29 dB optical power budget could be realized even without the use of a PDFA.

4. Conclusion

We demonstrated the feasibility of an IM/DD time-and-polarization-division-multiplexed (TPDM) passive optical network employing an EML transmitter boosted with PDFA and APD receivers to achieve 29 dB optical power budget with more than 4 dB excess margin. The system was realized by polarization-multiplexing two 100 Gbit/s PAM-3 channels decoded as duoternary at the receiver side to match analog bandwidth of available components, which at the same time simplifies decoding DSP and mitigates equalization-enhanced noise.

5. References

[1] R. Bonk and T. Pfeiffer, "New Use Cases for PONs Beyond Residential Services," Proc. OFC 2022, p. Tu2G.1.
[2] R. Bonk *et al.*, "Perspectives on and the road towards 100 Gb/s TDM PON with intensity-modulation and direct-detection," JLT **15**, 518-526 (2023).
[3] D. Che, *et al.*, "200Gb/s Bi-Directional TDM-PON with 29-dB Power Budget," Proc. ECOC 2021, p. We4F.1.
[4] R. Rosales *et al.*, "Dispersion Tolerant 200 Gb/s Dual-Wavelength IM/DD Transmission with 33dB Link Budget…," Proc. ECOC 2023, p. We.C.1.2.
[5] B. Koch *et al.*, "40-krad/s Polarization Tracking in 200-Gb/s PDM-RZ-DQPSK Transmission Over 430 km," in IEEE PTL **22**, 613-615 (2010).
[6] C. Doerr, "Link budget study of DP-PAM4 for 800G-LR," IEEE P802.3df," July 2022, https://www.ieee802.org/3/df/public/22_07/doerr_3df_01_2207.pdf.
[7] T. Hirokawa et al., "Analog Coherent Detection for Energy Efficient Intra-Data Center Links at 200 Gbps Per Wavelength," JLT **39**, 520-531 (2021).
[8] N. Dubrovina *et al.*, "Record High Power 13dBm Electro-Absorption Modulated Laser for 50G-PON," Proc. ECOC 2022, p. Th1E.6.
[9] R. van der Linden *et al.*, "Demonstration and application of 37.5 Gb/s duobinary-PAM3 in PONs," Proc. OFC 2017, paper Tu3G.4.
[10] V. Houtsma *et al.*, "100 GBd Dispersion-Tolerant Downstream PON with 35 dB Power Budget using APD…," Proc. ECOC 2023, p. We.C.1.1.
[11] D. A. Fishman and J. A. Nagel, "Degradations due to stimulated Brillouin scattering in multigigabit intensity-modulated…," JLT **11**, 1721-1728 (1993).
[12] C. Henry, "Theory of the linewidth of semiconductor lasers," IEEE JQE **18**, 259-264 (1982).
[13] P. Kabal and S. Pasupathy, "Partial-Response Signaling," IEEE Trans. Commun. **23**, 921-934 (1975).
[14] Q. Hu and R. Borkowski, "510 Gbit/s Net Bitrate IM/DD Link Enabled by 200 GBd Precoded Duooctonary…," Proc. ECOC 2023, p. Th.C.1.7.