Real-Time 100 Gb/s PAM-4 for Access Links with up to 34 dB Power Budget

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***Abstract*—The growing demand for broadband access networks keeps motivating research for higher capacity in both wired and wireless access networks. Recently, the recommendation for 50G-PON with conventional NRZ modulation has been published. Bidirectional point-to-point access networks, also known as BiDi, used in mobile xHaul, are standardized up to 50 Gb/s with PAM-4 as modulation format. The evolution in view of a next generation 6G wireless encourages research towards higher bitrates for fronthaul systems. Hence, there is interest for having single channel BiDi links with a bitrate of at least 100 Gb/s. In this paper we experimentally evaluate four possible IMDD transceiver schemes suitable for optical access applications in the O-Band that can cover BiDi link losses up to a bitrate of 100 Gb/s using PAM-4. We employ an EML with either a 25G-based APD or an optically preamplified p-i-n photodiode (PD) with low-complexity FFE equalization and achieve a real-time power budget of 23.7 dB, just above BiDi B- loss class. By adding an optical booster, we demonstrate up to 34 dB power budget, exceeding with enough margin the highest BiDi class B loss of 25 dB.**

***Index Terms*—Point to point, bidirectional, optical access, real-time, PAM-4, IMDD, APD, SOA+PIN, EML, SOA**

I. Introduction

In view of the increasing capacity demand for broadband optical access networks, both IEEE and ITU-T have published a recommendation for point-to-multipoint passive optical networks (PON) systems with up to 50 Gb/s capacity [1], [2]. Both standardization bodies have also released a recommendation for higher speed bidirectional, single fiber, point-to-point optical access system (HS-PtP), also known as BiDi, with a nominal rate up to 50 Gb/s for mobile or business applications [3]. While these bitrates are sufficient for current and near future systems, upcoming network requirements like 6G mobile might involve 100 Gb/s or higher bitrate links [4], [5].

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The modulation format adopted for 50G-PON (ITU-T G.9804.3) is conventional two level non-return to zero (NRZ). In order to achieve the large power budgets of PON (up to 35 dB), the system uses optical amplification at the optical line terminal (OLT) transmitter (Tx) and digital signal processing (DSP) at the optical network unit (ONU) receiver (Rx) [6]. Given the bandwidth (BW) requirement for two-level NRZ modulation, it is natural to consider that PON standards with bitrates higher than 50 Gb/s might employ multilevel formats with either direct or coherent detection [4], [7]. BiDi PtP links (ITU-T G.9806) require power budgets up to 25 dB and cover a fiber length of up to 40 km. In the latest amendment, the recommendation indicates that the modulation format for 50 Gb/s is 4-level Pulse Amplitude Modulation (PAM-4). The extension towards a single-channel 100 Gb/s BiDi link has already shown interest from network operators and it is probable that PAM-4 modulation will be reused [8], [9]. In addition, PAM-4 has been successfully applied in data centers for 200 Gb/s (4x50 Gb/s), and 400 Gb/s (4x100 Gb/s or 8x50 Gb/s) applications with fiber links up to 10 km.

There are several approaches reported in the literature concerning PAM-4 for 100 Gb/s access networks. In [10] and [11], power budgets of 29 dB and 24 dB after 50 km and 40 km transmission respectively were demonstrated with a 13 GHz directly modulated laser (DML) [10] and an 18 GHz electro-absorption modulated laser (EML) Tx [11] with Nyquist pulse-shaping. Both experiments used a semiconductor optical amplifier (SOA) pre-amplified Rx followed by constant modulus algorithm (CMA), Volterra nonlinear equalization (VNLE), and decision-directed least-mean-square (DD-LMS) DSP. Authors in [12] added a complex linear and nonlinear Tomlinson-Harashima Precoder (THP) before the Nyquist shaping together with decision feedback equalizer (DFE) and VNLE in Rx to obtain a 34 dB power budget in a BW limited system (15 GHz). A flexible-rate PON with both NRZ and PAM-4 modulations is proposed in [13] and extended with probabilistic shaping in [14], [15], demonstrating a 31.5 dB power budget with an SOA pre-amplified Rx and 23-tap feed forwa rd equalizer (FFE) and 5-tap DFE. With the aim to keep the complexity at the OLT, the authors in [16] employed a digital chromatic dispersion (CD) pre-compensation allowing operation in C-band and a sophisticated IQ modulator. At the ONU, they used either VNLE or a square-root like function as non-linear equalizer and measured up to 29 dB power budget. Also in C-band, a power budget of 30.5 dB was demonstrated in [17] with a polarization diversity coherent Rx aided with

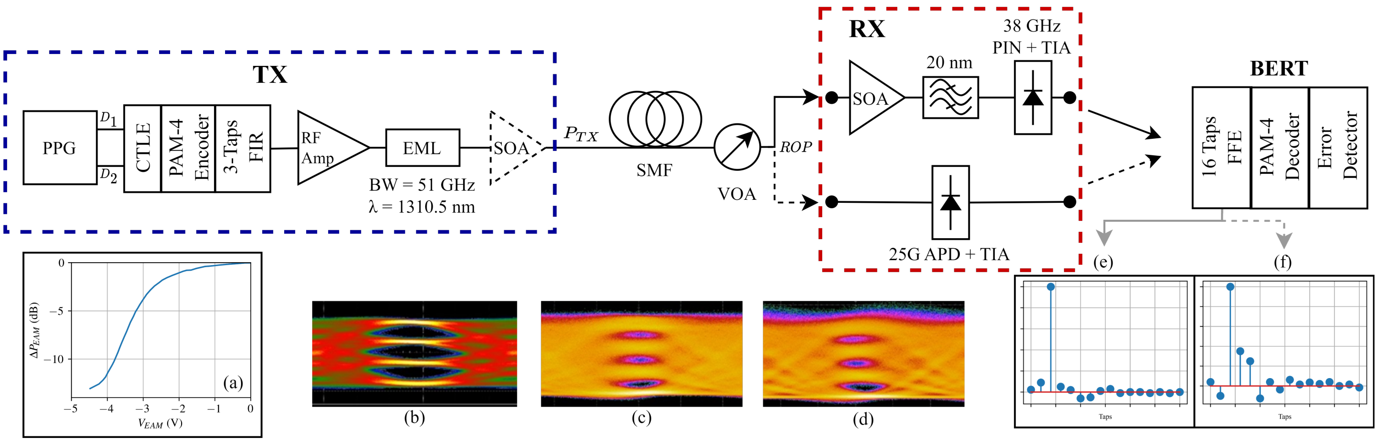

Fig. 1. Experimental setup. (PPG: Pulse Pattern Generator, CTLE: Continuous Time Linear Equalizer, FFE: Feed-forward Equalizer, EML: Electroabsorption-Modulated Laser, SOA: Semiconductor Optical Amplifier, SMF: Single Mode Fiber, VOA: Variable Optical Attenuator, APD: Avalanche Photodiode, TIA: Transimpedance Amplifier, BERT: Bit Error Rate Tester). Insets show: (a) EAM normalized transmission curve for a DFB current of 40 mA; eye-diagrams (b) after PAM-4 encoder (c) after EML and (d) after booster SOA; Rx FFE tap values for (e) SOA+PIN and (f) APD receiver

offline maximum-likelihood sequence estimation (MLSE) and a Tx with a 30 GHz EML amplified by an external SOA. While coherent detection can increase the Rx sensitivity and compensate for CD, few demonstrations have been carried out in the O-Band [18]. To simplify the coherent detection, authors in [19] propose a carrier-suppressed polarization division multiplexed PAM-4 with a Kramers-Kronig Rx and reports a 29 dB power budget after 25 km with offline processing and with a Tx based on Mach-Zehnder modulator (MZM). With the exception of [16] and [17], all experiments are carried out in the O-Band to reduce the effect of CD. For the same reason, to cover all the required fiber distances, the wavelength plan for 50G BiDi is allocated in the O-Band (1314 nm for DS and 1289 nm for US). Besides [17] employing a coherent Rx, the rest utilize a direct-detection (DD) scheme, more precisely an optically pre-amplified Rx, and all use offline DSP. In contrast, authors in [20] present DSP-free real-time measurements still with a pre-amplified Rx and a high BW MZM realizing 29 dB optical budget with a Praseodymium-doped fiber amplifier (PDFA) booster at the OLT. In [21], the MZM is replaced by an EML with drive signal pre-emphasis, and the optical budget measured is 21.5 dB and 30 dB without and with a PDFA booster amplifier respectively. While the benefit of optical amplification at the OLT is evident in [20], [21], the PDFA is a bulky device and currently not considered suitable for the low cost, massive volume production necessary for fiber access. Other low-noise optical amplifiers in O-band have been demonstrated, such as Raman or Bismuth-doped (BDFA) [22]. However these are primarily research works which, require a substantial fiber length in order to provide gain, making them difficult to integrate and deploy.

In [23] we presented a real-time, optically amplified, 100 Gb/s system using PAM-4 modulation with up to 34 dB optical budget. In this paper, we extend the results when no optical amplification is in place, achieving 21 dB optical budget with a 25G-class avalanche photodiode (APD) Rx after 40 km transmission at a hard-decision forward error correction (HD-FEC) bit error rate (BER) threshold of 10^{-2} (LDPC(17280,14592), as defined in [2]). Such a link budget is suitable for the BiDi application, where there is no large excess loss from optical split as seen in PON. We employ simple components and DSP suitable for a realistic and deployable optical access system. We use a PAM-4 encoder chip and a large BW EML to get a high quality optical eye. In the optically amplified case, we employ a commercial O-band SOA rather than doped fiber optical amplifiers. At the Rx, we work only with a simple 16-taps T-spaced FFE to compensate for the APD BW limitation and achieve a Rx sensitivity of –16.2 dBm at the HD-FEC threshold, allowing enough power budget for BiDi class A (20 dB). By replacing the APD with an SOA+PIN, we can improve the Rx sensitivity to almost –22 dBm, which gives enough power budget for BiDi class B (25 dB). If we further boost the Tx signal and consider soft-decision (SD) FEC threshold of $2\cdot10^{-2}$ [24], we achieve 29 dB and 34 dB power budget with APD and SOA+PIN Rx, respectively. To the best of our knowledge, these results are the highest power budgets reported with and without optical amplification for a 100 Gb/s PAM-4 IMDD real-time setup and demonstrate the feasibility for a single wavelength 100 Gb/s BiDi link. The rest of the paper includes the detailed description of the experimental setup, followed by the analysis and discussion of the results, and a final section summarizes the main findings.

II. Experimental Setup

The experimental setup is shown in Fig. 1, whereby two channels are used from a pulse pattern generator (PPG) with each channel being a pseudorandom bit sequence (PRBS) $2^{11}-1$ generated with a different seed. The two bit streams enter an analog PAM-4 encoder device with a continuous time linear equalizer (CTLE) and 3-tap FFE built-in equalizer (typically used to compensate for the instrument cables). The device does not include a feedback loop with the output signal, so it has to be manually adjusted. The resulting four-level signal is then amplified to 2 V_{pp} in order to drive a 1310.5 nm wavelength EML (51 GHz 3-dB BW).

The distributed feedback (DFB) laser and electroabsorption modulator (EAM) in the EML are biased at 40 mA and

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TABLE I
ROSA PARAMETERS

Parameter [Unit]	PIN+TIA	APD+TIA
3-dB BW [GHz]	38	21
Responsivity [A/W]	0.8	6.5
Multiplication factor	1	10

−3.03 V respectively and the output power (P_{Tx}) is 5.3 dBm after modulation. The EAM voltage is chosen after characterizing the device absorption against bias behavior, as seen in Fig. 1(a). In order to achieve a high optical budget, an O-band SOA boosts the signal resulting in an optical signal-to-noise ratio (OSNR) >37 dB (0.1 nm). The SOA, which has a gain of 16 dB and noise figure (NF) of 7 dB, is a discrete component in our experiments but could in principle be monolithically integrated with the EML [25], [26]. The launched 50 GBaud PAM-4 optical signal has an outer extinction ratio (ER) of 6.7 dB and 5.6 dB before and after the SOA, respectively.

After different lengths of singe mode fiber (SMF), a variable optical attenuator (VOA) controls the power into the Rx and allows variation of the optical path loss. The loss of the diplexers used in the transceivers to separate Tx and Rx wavelengths is not explicitly taken into account and it is considered as part of the overall link budget.

The Rx is either a 25G-class APD or an SOA (gain=15 dB and NF=7 dB) followed by a 20 nm optical bandpass filter centered at 1310 nm and a 38 GHz p-i-n PD. Both PDs have an integrated linear transimpedance amplifier (TIA) and are packaged into a receiver optical subassembly (ROSA). Table I summarizes the main parameters of the two devices. In our tests, the SOA in the Rx is also a separate component, however it can be integrated into an SOA+PIN as has been demonstrated in [27]. The detected electrical signal then passes through a 16-tap T-spaced FFE embedded in the bit error rate tester (BERT), which compensates for the BW limitation of the APD and the cables. Finally, the PAM-4 signal is decoded and the bit error ratio (BER) is computed in real-time in the error detector (ED).

III. EXPERIMENTAL RESULTS

A. Non-amplified transmitter

In the simplest system tested, we directly detect the EML generated PAM-4 optical signal with an APD+TIA after several lengths of SMF. Our objective here is to determine if this unamplified link can achieve a link budget of at least 20 dB (BiDi class A). We firstly manually adjust the Tx pre-equalizer to get the maximum eye-aperture of the optical signal, i.e. the pre- and post-cursor of the FFE. Afterwards, we compute the optimum tap values for the Rx equalizer following an offline least-mean square (LMS) in BtB. The ED FFE has a fixed main cursor, so we are constrained to work with two precursors. As seen in inset (f) of Fig. 1, we effectively use only two post-cursors in the Rx equalizer. We then carry out small adjustments to the coefficients for best BER at a received optical power (ROP) of -3 dBm. The tap values obtained under these conditions are then left constant for all the measurements.

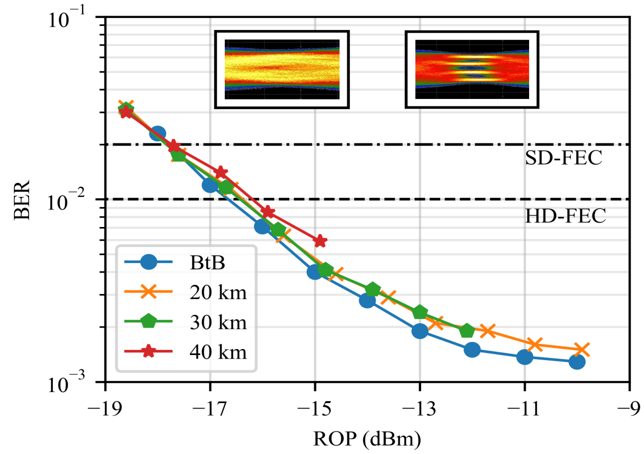

Fig. 2. BER vs. ROP for unamplified Tx and APD-based Rx at several fiber lengths. Dashed and dotted lines indicate HD-FEC ($1{\cdot}10^{-2}$) and SD-FEC ($2{\cdot}10^{-2}$) threshold. Insets report the received electrical signal before and after the equalizer.

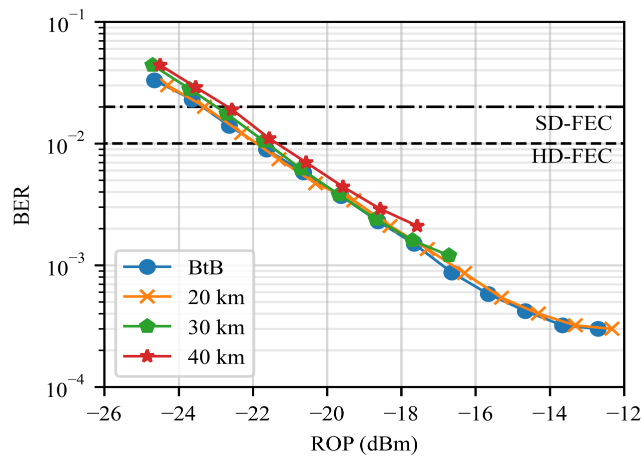

Fig. 3. BER vs. ROP for unamplified Tx and SOA+PIN-based Rx at several fiber lengths.

Fig. 2 shows the BER results against ROP for back-to-back (BtB), 20 km, 30 km, and 40 km of SMF. The Rx sensitivities are -16.6 dBm and -16.2 dBm at BtB and after 40 km of SMF respectively at a hard decision FEC (HD-FEC) threshold of 10^{-2} (LDPC (17280, 14592) as defined in ITU-T [2]). Even if current 50 Gb/s BiDi is defined with Reed-Solomon (RS) FEC codes, we expect that future recommendations will include low-density parity check codes (LDPC) as used in PON. The small amount (0.4 dB) of optical path penalty (OPP) measured can be attributed to the emission wavelength being close to the fiber zero-dispersion wavelength and the FFE which partially compensates any intersymbol-interference (ISI) caused by the fiber CD. We also observe a BER floor at $2{\cdot}10^{-3}$ which we attribute to the electrical noise in the Tx and Rx components and the limited equalization at the Rx. As shown in [28], an optimized design of the APD+TIA can in principle bring the

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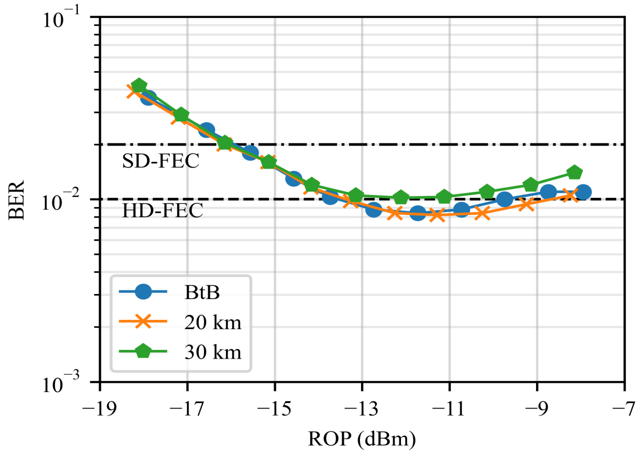

Fig. 4. BER vs. ROP for amplified Tx and APD-based Rx at several fiber lengths.

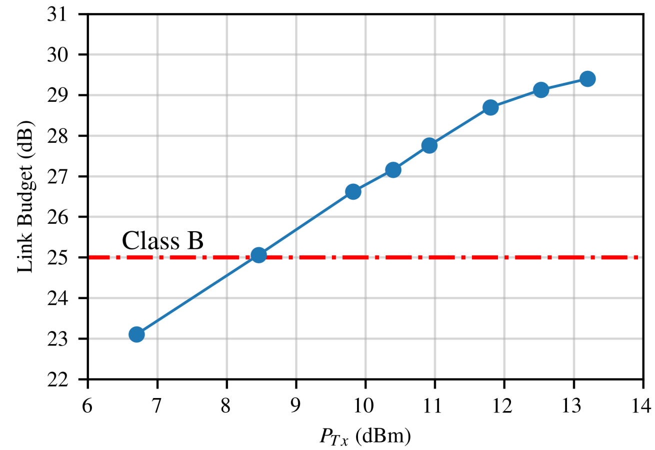

Fig. 5. Link budget vs. transmitted power for amplified Tx and APD-based Rx after 20 km at SD-FEC ($2{\cdot}10^{-2}$) threshold.

BER floor to a value as low as 10^{-8}. Considering that the P_{Tx} is +5.3 dBm, an optical budget of 21.5 dB is achieved which gives 6.5 dB and 1.5 dB margin for BiDi class S and class A, respectively. If we consider an SD-FEC threshold of $2{\cdot}10^{-2}$ then the Rx sensitivity after 40 km of SMF is -17.7 dBm which produces a power budget of 23 dB, enough for class B-. Hence, with an EML with enough BW and a simple equalized 25G-class APD, a BiDi link can be realized with 100 Gb/s/λ.

We then replace the APD for a pre-amplified SOA+PIN configuration and optimize the FFE coefficients at the Rx, always in BtB. In this case, the Rx has enough BW ($\sim$38 GHz) and the FFE is mainly used for compensating the cables. The tap values obtained under these conditions (Fig. 1(e)) are then kept constant for all the measurements. Fig. 3 plots the BER against the ROP in BtB and after 20 km, 30 km, and 40 km of SMF. Compared to the APD, the Rx sensitivity at HD-FEC threshold improves to -21.8 dBm in BtB and to -21.4 dBm after 40 km. The OPP is only 0.4 dB since the accumulated CD is small, while the BER floor reduces to $3{\cdot}10^{-4}$ due to the high BW Rx. With P_{Tx}=+5.3 dBm, the optical budget is increased to 26.7 dB, which gives enough margin for Class B for BiDi; if SD-FEC is assumed, the optical budget is improved by 1.5 dB to 28.2 dB. Thus, the SOA+PIN with practically no electrical equalization can be an alternative to cover the highest BiDi loss class at the longest transmission distance within the scope of [3].

B. Optically amplified transmitter with APD-based receiver

Building on the successful application of SOA pre-amplification described in the previous section, we also investigate their use in this 100 Gb/s link as a booster. We thus add an SOA to the Tx to produce a P_{Tx}=+10.9 dBm with 210 mA bias current. We modify the pre-equalizer FFE coefficients in the PAM-4 encoder and reduce slightly the EAM bias to -2.95 V to get the maximum eye-aperture of the optical signal after the SOA. In addition, after an initial offline optimization of the FFE taps in the Rx with LMS, we found out that some further manual fine-tuning of the taps enabled us to obtain the lowest BER at an ROP of -13 dBm in BtB. Then, we measure the BER in BtB and after 20 km and 30 km as shown in Fig. 4.

We notice that the BER floor has climbed very close to 10^{-2}, which is mainly due to the optical noise added by the SOA. The BER floor is even higher than 10^{-2} after 30 km and at 40 km the noise level is too high to detect the signal. We anticipate that the BER floor can be lowered by using a higher BW APD+TIA, as in [28]. However, such a BER floor still needs to be quantified when the optical signal is amplified and includes optical noise.

At the HD-FEC threshold of BER=10^{-2}, the Rx sensitivity in BtB and after 20 km is -13.7 dBm and -13.4 dBm, respectively. While the Rx sensitivity is degraded compared to the non-amplified case because the latter detected a cleaner signal, P_{Tx} is 5.6 dB higher with the SOA booster, and a link budget of 24.3 dB is attained. However, the HD-FEC threshold is very close to the BER floor and working under such condition will constrain the system performance and operation range. We expect that more complex equalization techniques can help to improve the Rx sensitivity, as shown [12], where an optically amplified system with Volterra and nonlinear DFE gained at least 2 dB in contrast to FFE+DFE only. Furthermore, if we consider the results published in [28] and include the penalty measured when the Tx is optically amplified (3 dB), at HD-FEC threshold we can expect a 2 dB Rx sensitivity gain with a 50GBaud APD+TIA.

With SD-FEC, the Rx sensitivities improve to -16.2 dBm and -16.1 dBm in BtB and after 20 km respectively and a link budget of 27 dB is measured. For such pre-FEC BER level, we get a Rx sensitivity of -16 dBm after 30 km. Although the link budget value obtained is enough to cover the highest loss BiDi class, the transmission distance of 40 km cannot be achieved. The link budgets obtained with this system configuration are around 2 dB lower than the EML with SOA+PIN described in the previous section. We mainly explain this difference by the limited BW APD+TIA and the limited equalization used. If the expected gain from using a 50G APD with an amplified Tx is confirmed, then the link budgets of the two configurations

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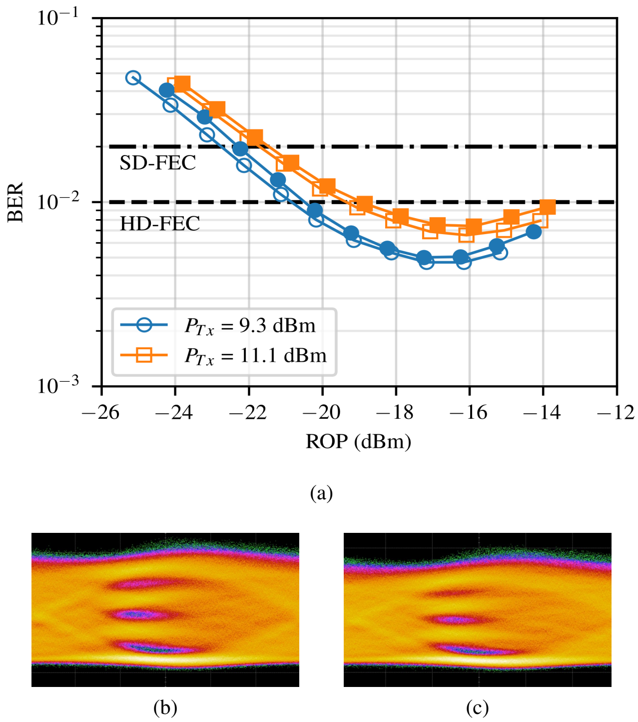

Fig. 6. (a) BER against ROP for amplified Tx and amplified Rx in BtB (empty markers) and after 20 km (solid markers) with P_{Tx} = 9.3 dBm and P_{Tx} = 11.1 dBm. Eye diagrams at BER floor measured before the PD with P_{Tx} = (b) 9.3 dBm and (c) 11.1 dBm

become comparable.

We then evaluate several P_{Tx} by changing the corresponding SOA bias and measure the Rx sensitivity at BER=2·10^{-2} after 20 km. Fig. 5 plots the link budget computed at different P_{Tx}. Even if we are close to zero dispersion wavelength and we expect self-phase modulation to cause limited pulse spreading, we still constrain P_{Tx} at +13.4 dBm to avoid nonlinearities in the fiber [21], [29]. From Fig. 5, we observe that with P_{Tx} = +8.5 dBm (with a corresponding Rx sensitivity of -16.6 dBm), even the highest BiDi loss class B can be achieved. These results show that an integrated EML+SOA with relatively small gain and moderate P_{Tx} is suitable for BiDi links, guaranteeing at the same time additional margin if P_{Tx} is increased.

C. Optically amplified transmitter with SOA+PIN receiver

For completeness of the study, we also test the system with optical amplification in Tx and Rx up to 20 km. We set the P_{Tx} to +9.3 dBm and optimize the Rx-side FFE coefficients in BtB for minimum BER at ROP of -17 dBm. Fig. 6(a) shows the BER plots versus ROP. The eye diagrams in Fig. 6(b) and 6(c) clearly show how the four levels of the optical signal get distorted when we increase the transmitted power. At HD-FEC threshold, the ROP is -20.8 dBm and -20.6 dBm in BtB and after fiber, respectively, which together with the Tx optical power gives a link budget of 29.9 dB. Interestingly, the Rx sensitivity and power budget achieved are only 1.5 dB and 0.6 dB lower with respect to those reported in [17] with coherent amplification and offline processing, although we note again that the experiments in [17] are done in C-Band.

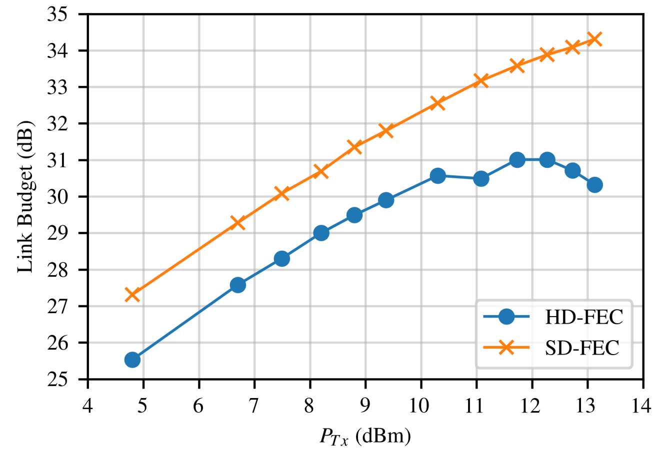

Fig. 7. Link budget against transmitted power at FEC threshold of 10^{-2} and 2·10^{-2}.

The measured Rx sensitivity is almost 2 dB better than the real-time results reported in [20] with PDFA as booster. We get such improvement by using a high-BW EML and by fine-tuning the Tx equalizer to obtain the maximum eye aperture after the SOA.

If we consider a SD-FEC threshold of 2·10^{-2}, the ROP improves by almost 2 dB to -22.3 dBm after fiber and we can get a link budget of 31.8 dB. A more complex DSP in Rx and further adaptive optimization can provide additional gain. Two more observations can be made from Fig. 6(a). Firstly, for ROP values higher than -17 dBm the BER increases because, at such ROP, the optical signal starts to saturate the TIA and distorts the highest level of the signal. This could be avoided by an optimized design of the TIA. The second observation is the BER floor appearing at 8·10^{-3} which can be explained by the optical ASE noise in the Rx signal. In [23], we report that changing the Rx optical filter for one with 1 nm BW, the BER floor reduces to 5·10^{-3}.

We then vary the SOA booster gain to find the maximum link budget. Fig. 7 plots the link budget versus P_{Tx} at HD-FEC threshold of 10^{-2}. We constrain the P_{Tx} to around +13.4 dBm in order to avoid nonlinearities in the fiber [29], [30]. Similarly to the results in Section III-A, class B can be attained with P_{Tx}=+5 dBm and still have 1 dB margin. At a target BER of 10^{-2} we achieve a maximum link budget of 31 dB, which gives 6 dB further margin for class B. For P_{Tx}>+12.3 dBm the link budget decreases and we see the reason is a higher BER floor level when we increase P_{Tx}, as shown in Fig. 6a, resulting in a degradation in the Rx sensitivity. We can explain this by SOA nonlinearities causing distortions in the signal. We anticipate that part of this penalty could be eliminated by using a more complex DSP at the Rx. For a SD-FEC threshold of 2·10^{-2}, we measure a maximum link budget of 34.3 dB at P_{Tx}=+13.4 dBm. These values are excessive for the BiDi application and the system with optical amplification in the Tx and in the Rx seems also too complex for such an application. However, it can provide a valuable reference on the maximum achievable link budgets.

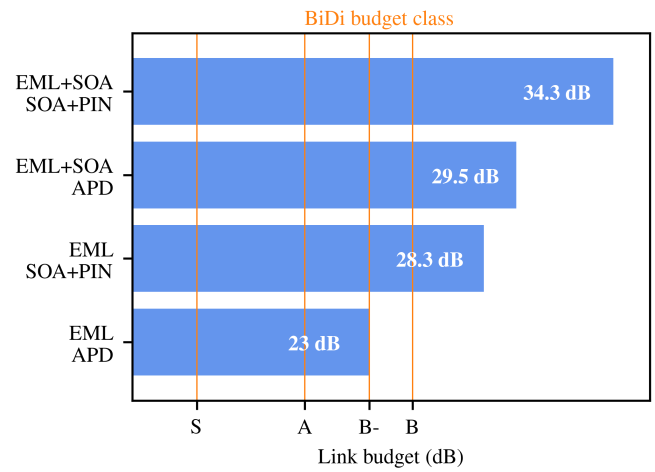

Fig. 8. Summary of achieved link budgets with the architectures tested and the corresponding BiDi loss classes they can achieve after 20 km at SD-FEC threshold

We remark that, due to our Tx working only at 1310.5 nm, the link budgets are computed considering a maximum measured total CD of 4.4 ps/nm. Bidirectional systems employ two wavelengths (one per direction), which for the 100G application are envisaged to be centered at 1304 nm and 1309 nm [31]. For the lowest wavelength, the minimum and maximum total CD are -75.31 ps/nm and 14.65 ps/nm. The negative CD and the chirp of the Tx produce a limited OPP the path loss and could even improve the Rx sensitivity while the positive CD is low enough to limit the OPP below 1 dB. The minimum and maximum CD at 1309 nm are -56.16 ps/nm and 32.78 ps/nm respectively. In a similar way as to 1304 nm, the total negative CD will cause a negligible OPP. However, the highest CD can induce ISI and produce an OPP up to 2 dB. If we consider a drift of ± 1 nm, then the highest CD raises to 37 ps/nm, which can increase the OPP to 2.5 dB [31].

In Fig. 8 we summarize the maximum power budget we experimentally demonstrate in this paper and relate them to the optical link budget classes for BiDi. A 100G PAM-4 PtP can be done with a single EML and a 25G-APD with simple FFE equalization for realizing Class B-. The highest loss Class B is attained by using an SOA either at the Tx or at the Rx. For the latter case, a high margin can be obtained by also adding an SOA booster, but this might not be necessary for the BiDi application.

IV. Conclusion

We demonstrate a 100 Gb/s single channel with and without optical amplification in Tx and with either APD or SOA+PIN based Rx in real-time with PAM-4 modulation. We use simple O-band components suitable for optical access applications, and obtain Rx sensitivities as low as -22 dBm at HD-FEC BER threshold of 10^{-2} by optimizing the Tx eye quality in real-time and with ISI-compensation based only on short FIR filters. In order to compensate for BW limitation, we employ a low-complexity real-time 16 tap T-spaced FFE at the Rx. For the pre-amplified Rx we work as far as possible in the SOA linear region. In a scenario without optical amplification in Tx, at a HD-FEC, we achieve sensitivities of –16.2 and –22 dBm for 25G-APD and SOA+PIN Rx respectively after 40 km. With a Tx launch power of +5.3 dBm, the corresponding power budgets obtained are 21.5 dB and 27.3 dB, which can meet (with margin) the BiDi budget classes A and B, respectively.

By adding an SOA booster in Tx, the Rx sensitivities at HD-FEC change to –13.4 dBm and –20.4 dBm with 25G-APD and SOA+PIN respectively. Power budgets up to 29.5 dB can be realized. Moreover, at a SD-FEC BER limit of $2{\cdot}10^{-2}$ and increasing P_{Tx} up to +13.4 dBm, we reach, with simple equalization, a real-time 100 Gb/s PAM-4 record link budget of 34.3 dB. These results show a simple approach to realize 100 Gb/s access links for PtP BiDi applications being discussed in standardization bodies such as the ITU-T and IEEE.

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