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Real-Time 100Gb/s Downstream PAM4 PON Link with 34 dB Power Budget

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Abstract *We experimentally demonstrate in real-time a 34dB PON power budget, exceeding E1 ODN class, with 100Gb/s PAM4 modulation using an amplified O-Band EML plus receiver-side optical amplification and only low complexity FFE equalization. ©2022 The Author(s)*

Introduction

Driven by the growing demand of broadband access, passive optical networks (PON) continue the evolution towards higher capacity. Both IEEE and ITU-T have standardized PON systems with capacity up to 50 Gb/s using conventional non-return to zero (NRZ) modulation format [1]. Given the bandwidth (BW) requirement for two-level NRZ modulation, it is natural to consider that PON with bitrates higher than 50 Gb/s might employ multilevel formats with either direct or coherent detection [2]. In data centers, 4-level pulse amplitude modulation (PAM4) has been successful for 200 Gb/s (4x50 Gb/s) and 400 Gb/s (4x 100Gb/s) applications. Hence, PAM4 in PON is somewhat of a hot-topic, with several research groups recently evaluating it as a candidate modulation format for future PON, which has as main technical challenges the low cost constraint and high loss budget requirement.

There have been several different approaches reported in the literature concerning PAM4 for 100 Gb/s PON. In [3] and [4], a power budget of 29 dB and 24 dB respectively, was demonstrated with pre-equalization and nonlinear equalization at the receiver (Rx) and 13 GHz BW DML [3] and 18 GHz BW electro-absorption modulated laser (EML) based transmitter (Tx) [4]. Also, with a limited BW system (15 GHz), a 34 dB power budget was obtained in [5] with a relatively complex nonlinear Tomlinson-Harashima precoding and Volterra equalization. With digital pre-compensation and a sophisticated IQ modulator at the OLT, the authors in [6] measured more than 29 dB power budget in the C-band with nonlinear adaptive equalization at the Rx. Also in C-band but with a polarization diversity coherent Rx, a power budget of 30.5 dB was demonstrated with the aid of offline post-processing and a 30 GHz EML amplified by an external SOA in Tx [7]. A flexible-rate PON with both NRZ and PAM4 is proposed in [8] demonstrating a 31.5 dB power budget with an SOA-pre-amplified Rx with 23-tap feed forward equalizer (FFE) and 2-tap DFE.

With the exception of [6] and [7], all experiments are carried out in the O-Band to reduce the effect of chromatic dispersion (CD). Besides [7] employing a coherent Rx, the rest utilize a direct-detection scheme. All previous studies have in common that they use optical amplification and offline advanced digital signal processing (DSP). In contrast, [9] presents DSP-free real-time measurements employing a MZM at the OLT realizing 29 dB optical budget with a Praseodymium-doped fiber amplifier (PDFA) at the OLT. However, the PDFA is a bulky technology and currently it is not considered suitable for the low cost, massive volume manufacturing necessary for PON. Furthermore, the MZMs are usually not employed in PON applications due to cost reasons.

In this paper we present a real-time 34 dB optical budget with 100 Gb/s PAM4 modulation using simple components and DSP suitable for a realistic and deployable 100G-PON system, and in particular employing a commercial O-band SOA rather than doped fiber optical amplifiers. To the best of our knowledge, this is the highest power budget reported for 100 Gb/s with a real-time set-up. We use a PAM4 encoder and a large BW EML to get a high quality optical eye before a 20 km fiber link. By taking advantage of optical amplification, we can improve the Rx sensitivity sufficiently to achieve a PON power budget class E1 (33 dB) with some margin. Furthermore, we use only a simple 16-taps T-spaced FFE at the Rx.

Experimental Setup

Figure 1 shows the experimental setup whereby two channels are used from a pattern generator (PG) with each channel being a PRBS 2^{11}-1 with a different seed. The two bit streams enter an analogue PAM4 encoder device with a CTLE and 3-tap FFE built-in equalizer (typically used to compensate for the instrument cables) and the resulting 4-level signal is then amplified to drive a 1310.5 nm wavelength EML (51 GHz 3-dB BW). The DFB and EAM in the EML are biased at 40 mA and 3.03 V respectively and an O-band SOA then boosts the optical power (with >37dB OSNR). The SOA, which has a gain of 16 dB and

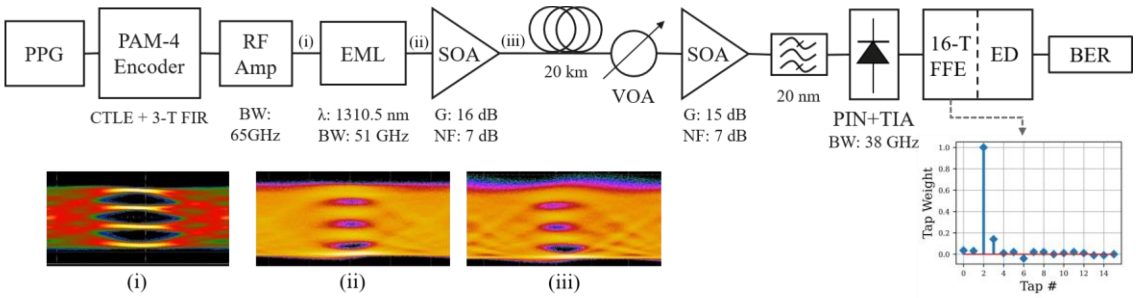

Fig. 1: Experimental setup. The insets show the eye-diagram evolution at the Tx: (i) electrical before the EML, (ii) optical after the EML, and (iii) after the SOA. We also show the Rx FFE tap coefficient values.

NF of 7 dB, is a discrete component but could in principle be monolithically integrated with the EML. The launched 50 GBaud PAM4 optical signal has an outer extinction ratio (ER) of 5.6 dB. After 20 km of single mode fibre (SMF), a variable optical attenuator (VOA) emulates the power splitters of the PON ODN and controls the power into a pre-amplified Rx. The Rx consists of an SOA, a 20 nm optical bandpass filter (centred at 1310 nm), and a 38 GHz p-i-n photodiode (PD) with a linear transimpedance amplifier (TIA). The detected electrical signal then passes through a 16-tap T-spaced FFE embedded in the error detector (ED). Finally, the bit error ratio (BER) is computed in real-time.

Results

For an initial target of N1 budget class (29 dB), we set the Tx output power (P_{Tx}) from the SOA booster to +9.5 dBm. We optimized both the pre-equalizer in the PAM4 encoder and Rx-side FFE coefficients (plotted in fig.1) in optical back-to-back (BtB) for the lowest BER at a received optical power (ROP) of -17 dBm. We firstly adjusted manually the Tx pre-equalizer to get the maximum eye-aperture of the optical signal. Afterwards, we computed the optimum tap values for the Rx equalizer following an offline least-mean square (LMS) algorithm constrained to 2 precursors since the main cursor position is fixed in the ED FFE. As seen in the inset of Fig. 1, we effectively use only 1 post-cursor in the Rx equalizer. The tap values obtained under these conditions are then left constant for all the measurements.

Fig. 2 shows the BER plots versus ROP. The eye diagrams in Fig. 2b and 2c clearly show the 4-levels of the optical signal recorded at the BER floor (i.e. -17 dBm and -14 dBm for optical filter BW of 20 nm and 1 nm, respectively). There is a penalty of ~0.5 dB between the BER plots in BtB and after 20 km. This small penalty is expected, since we are working close to the zero-dispersion wavelength of the fibre. At a hard decision FEC (HD-FEC) threshold of $1 \cdot 10^{-2}$ (LDPC (17280, 14592) as defined in ITU-T [1]), the ROP is -20.4 dBm after fibre which together with the Tx optical power gives a link budget of 29.9 dB. In a bidirectional (BiDi) PtP scenario, these results give enough margin for the power budget required, i.e. 20 dB, and one of the amplifiers could even be omitted [9]. Interestingly, the Rx sensitivity and power budget achieved are only 1.5 dB and 0.6 dB lower respectively than those reported in [7] with coherent amplification and offline processing, although we note again that the experiments in [7] are done in C-Band.

If we consider a soft-decision FEC (SD-FEC) threshold of $2 \cdot 10^{-2}$, the ROP improves by almost 2 dB to -22.3 dBm and we can get a link budget of 31.8 dB which meets ITU PON N2 class (31 dB). A more complex DSP in Rx and further adaptive optimization can provide additional gain.

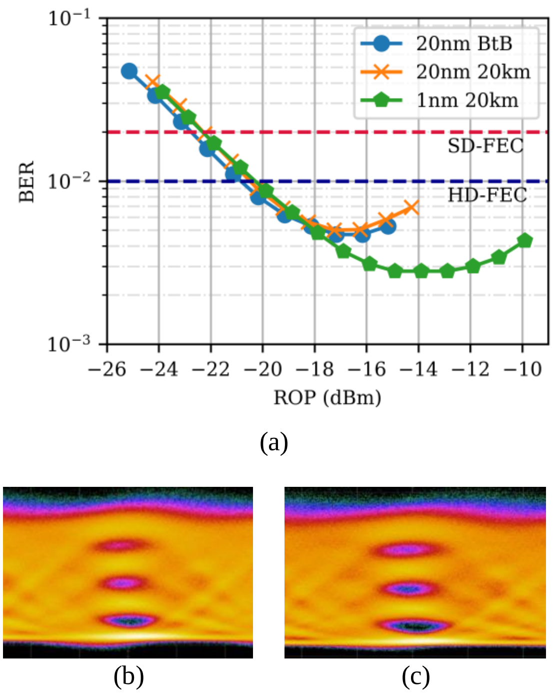

Fig. 2. (a) BER against ROP in BtB and after 20 km with optical filter BW of 20 nm and 1 nm; and eye-diagrams at BER floor measured before the PD with optical filter BW of (b) 20 nm and (c) 1 nm.

Two more observations can be made from Fig. 2. Firstly, for ROP values higher than -17 dBm, the BER increases for the 20nm optical filter cases and this is 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 ~$8{\cdot}10^{-3}$ which can be explained by the optical ASE noise in the Rx signal. If we change the Rx optical filter to one with 1 nm BW, the BER floor reduces down to $5{\cdot}10^{-3}$ as seen in Fig. 2. However, at 10^{-2} BER the ROP is almost identical for the two optical filter cases. For an integrated EML+SOA device at the Tx we expect temperature controlled operation will be necessary, hence an optical filter narrower than 20nm (e.g. 4nm) may be reasonable to use at the Rx. As an alternative for lower power budgets, the Rx could be simplified by using an APD-TIA with an optimized frequency response. As shown in [10] in BtB, this approach could reduce the BER floor for a 100 Gb/s PAM4 signal with an error floor as low as $1{\cdot}10^{-8}$.

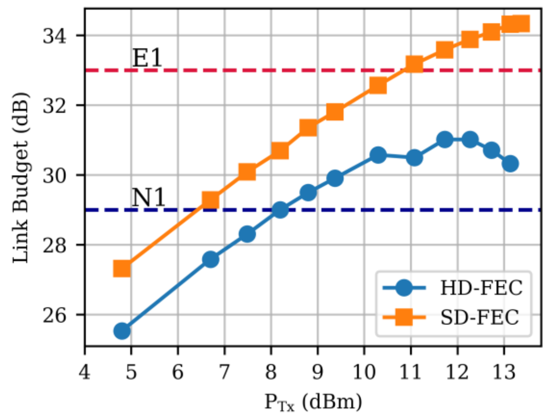

Fig. 3 (a) Link budget against P_{Tx} at FEC threshold of $1{\cdot}10^{-2}$ and $2{\cdot}10^{-2}$

Next, we vary the SOA gain at the Tx to find the maximum link budget. We left the 20 nm optical filter since there was no difference at the pre-FEC threshold levels. Fig. 3 plots the link budget versus P_{Tx} at FEC thresholds of $1{\cdot}10^{-2}$ (HD-FEC) and $2{\cdot}10^{-2}$ (SD-FEC). We constrain the P_{Tx} to around +13.4 dBm in order to avoid nonlinearities in the fibre as seen in [9]. At a target BER of $1{\cdot}10^{-2}$ we achieve a maximum link budget of 31 dB, enough for N2 class and with 2 dB margin for N1 class. For $P_{Tx} > 12.3$ dBm the link budget decreases and we see the cause in Fig. 4, which plots the BER against ROP for different P_{Tx}. We note that when increasing P_{Tx} the BER floor level increases and approaches $1{\cdot}10^{-2}$ and the Rx sensitivity degrades. 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 BER threshold of $2{\cdot}10^{-2}$, we measure a maximum link budget of 34.3 dB at P_{Tx} = +13.4 dBm. With SD-FEC, E1 budget class can be covered with P_{Tx} of +11 dBm. Higher P_{Tx} provides up to 1.3 dB margin to account for excess losses that might occur in the ODN. To the best of our knowledge, this is the first demonstration of E1 class and a record 34.3 dB optical budget for a single channel 100 Gb/s PON in real-time.

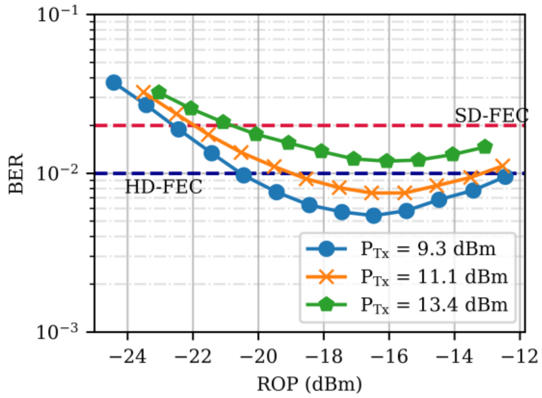

Fig. 4 BER against ROP at different P_{Tx}

Conclusions

To the best of our knowledge, we demonstrate the first downstream single channel 100 Gb/s PON in real-time with PAM4 modulation which meets E1 power budget class. We use simple O-Band components suitable for PON applications and a low-complexity real-time 16-tap T-spaced FFE at the Rx. At a pre-HD-FEC BER level of 10^{-2}, we achieve sensitivities close to -20.5 dBm by means of an SOA pre-amplified Rx. The Rx sensitivity measured is almost 2 dB better than the real-time results reported in [9] with a PDFA at Tx. We get such improvement by optimizing the Tx eye quality in real-time and using a high BW EML. We also work as far as possible in the linear region of the pre-amplified Rx. With a reasonable launch power of +9 dBm, the system meets N1 PON power budget class and with P_{Tx} as low as 0 dBm, the BiDi PtP power budget requirement (20 dB) is attained. Moreover, at a SD-FEC BER limit of $2{\cdot}10^{-2}$ and increasing P_{Tx} to +11 dBm, we reach PON budget class E1. By further amplifying P_{Tx} to +13.4 dBm, we accomplish, with simple equalization, a downstream record real-time 100 Gb/s PAM4 link budget of 34.3 dB.

These results show a simple approach to realizing 100 Gb/s access links for both the PtP and PON applications being discussed in standardization bodies such as the ITU-T and IEEE.

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