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Abstract: We evaluate TDEC and Rx sensitivity in a negative dispersion regime with 25G-class DML and EML modulated at 50 Gb/s. Results show that TDEC can effectively predict the performance of both transmitters for 50G-PON upstream.

1. Introduction

The ITU-T released the first version of recommendations for 50G-PON in 2021 [1]. Optical amplification at the OLT and digital signal processing (DSP) are essential components in 50G-PON to enable the high loss budgets. DSP, in particular, allows to compensate for the fiber transmission effects as well as for using lower bandwidth (BW) optical components [2]. In order to guarantee physical layer interoperability and ensure a high enough transmitter (Tx) quality with a specific equalization at the receiver (Rx), 50G-PON adapted the transmitter and dispersion eye closure (TDEC) metric from [3].

TDEC provides a Tx quality and transmission penalty metric by means of eye-diagrams captured with an oscilloscope and allows a prediction the performance of a Tx [3]. The 50G-PON recommendation defines TDEC for downstream (DS) with a 13-tap T-spaced FFE reference equalizer preceded by a 4th order Bessel-Thompson low-pass filter with 18.75 GHz 3-dB BW to emulate the frequency response of a 25G avalanche photodiode (APD) [4, 5]. Recently, TDEC has been defined for upstream (US) at 50 Gb/s, where some of the wavelengths (1260-1280 nm and 1290-1310 nm) can fall into the negative chromatic dispersion (CD) regime. In addition, although potential 50G US Tx devices are becoming commercially available, 25G components can be used to keep the cost low. It is then important to evaluate the effectiveness of TDEC with 25G Tx under negative CD.

In this paper we present, to the best of our knowledge, the first experimental investigation of TDEC in the negative CD regime for 50 Gb/s US with 25G direct modulated laser (DML) and electro-absorption modulated laser (EML). We relate TDEC with the link penalty measured from the Rx sensitivity when using an equalized 25G APD as Rx and show a linear relation between both variables for the two Tx. We also test a 40G Mach-Zehnder modulator (MZM) based Tx as reference. We show that TDEC can effectively predict the performance in the negative dispersion fiber link and the optical signal quality of the Tx.

2. Experimental Setup

Fig. 1 depicts the experimental setup. A pulse pattern generator (PPG) produces either a PRBS-15 for bit error rate (BER) measurement, or a short-stressed pattern random (SSPR) sequence for TDEC [1]. The electrical signal is adjusted to modulate the DML, then electro-absorption modulator (EAM) section of the EML, or MZM to produce an optical NRZ signal, which is subsequently sent through different lengths of single-mode fiber (SMF). The emission wavelengths for the DML and EML are 1293 nm and 1300 nm, respectively, while the light source for the MZM is an external cavity laser (ECL) emitting at 1310 nm. Both DML and EML are packaged in optical subassemblies and the measured extinction ratio (ER) is 4 dB for the DML and 6 dB for the EML. The low ER from the DML is due to non-optimal electrical connections. Table 1 summarizes the key parameter values for both studied Tx. The output power (P_{out}) from the DML is reported considering the expected insertion loss of the optical multiplexer (3.5 dB) included in the transmitter optical sub-assembly (TOSA). At Rx side, the optical signal is captured by a digital sampling oscilloscope (DSO) with an embedded digital 4th order Bessel-Thompson filter with 18.75 GHz BW. TDEC is then measured after applying a 13-tap T-spaced FFE, according to [1]. When computing the BER, a variable optical attenuator (VOA) limits the input power into an InP 25G APD, whose electrical output is then captured by the DSO and processed with a 13-tap T-spaced FFE followed by a 1-tap DFE. The equalizer coefficients were optimized following a zero-forcing (ZF) algorithm. By direct error counting, we calculate the average BER after 40 PRBS-15 sequences.

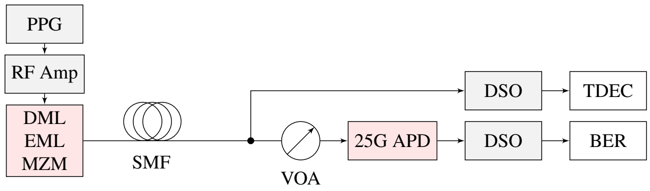


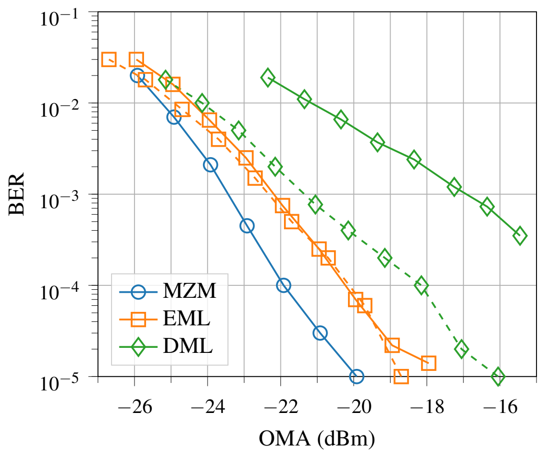
Fig. 1: Experimental setup

Table 1: Transmitter Parameters

Parameter	DML	EML
DFB I_{bias} (mA)	60	85
EAM V_{bias} (V)	-	1.9
Wavelength (nm)	1293	1300
Extinction Ratio (dB)	4	5.5
Output power (dBm)	+6.2	+4

3. Results

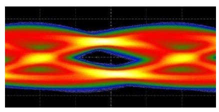
We firstly measure the BER against optical modulation amplitude (OMA). We use OMA to eliminate the difference in ER. Fig. 2a reports the results with solid lines in back to back (BtB) and dotted after SMF. The OMA at a pre-FEC target BER of 10^{-2} for the DML is -21.1 dBm. The reduced Tx and Rx BW, together with some electrical reflections still appearing in the signal, limited the Rx sensitivity. Also, the eye-diagram in BtB after equalization is skewed, as noticed in Fig. 2b. In comparison, the EML has a more symmetric eye in BtB as seen in Fig. 2c and, reflecting the eye-quality improvement, the measured OMA at 10^{-2} is lowerd to -24.4 dBm. We also test a full-BW MZM as benchmark with an ER of 6 dB. In this case, the Rx sensitivity improves to -25.2 dBm and the corresponding eye-diagram in BtB displayed in Fig. 2d is clearly more open than the other Tx devices.



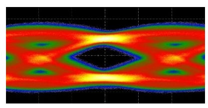
(a)

Table 2. Measured CD values

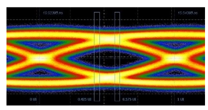
Distance	$\lambda = 1290$ nm	$\lambda = 1300$ nm
10 km	-24.2 ps/nm	-14 ps/nm
20 km	-44.7 ps/nm	-28 ps/nm
25 km	-57.6 ps/nm	-36 ps/nm



(b)



(c)



(d)

Fig. 2: (a) BER vs. ROP in BtB (solid) and after 20 km (dotted) for several Tx types using DFE-equalized 25G APD in Rx. BtB eye-diagrams of (b) DML, (c) EML, and (d) MZM

We then measure TDEC after capturing at least 20 consecutive waveforms with SSPR sequence to get repeatable and stable values. In BtB, the transmitter eye-closure (TEC) values we obtain are 5.2 dB, 2.3 dB, and 1.6 dB for DML, EML and MZM, respectively. The high TEC for the DML reflects its poor Rx sensitivity as well as its eye quality (Fig. 2b). More significantly, we notice that the variation in the TEC among the Tx correlates accurately with the Rx sensitivity. The TEC for DML is almost 3 dB higher than for the EML, and the Rx sensitivity difference between them is nearly the same (3.3 dB). Between the DML and MZM, the TEC and Rx sensitivity change 3.6 dB and 3.9 dB respectively and comparing the EML and MZM both variables differ by around 0.7 dB.

Fig. 3a plots the TDEC against the ROP for the DML and EML Tx. Each point corresponds to an additional 5km SMF spool up to a total length of 25 km (Table 2 shows the total measured CD). In BtB, the signal quality produced by each Tx measured with the TEC is reflected in their Rx sensitivity as described in the previous paragraph. The DML emits light below the zero-dispersion wavelength of the SMF. The interaction of the optical signal chirp with the negative CD (after 10 km and 25 km, the total accumulated CD is -24.2 ps/nm and -56 ps/nm respectively) results in a more open eye-diagram as the signal travels through the SMF. Hence, both TDEC and Rx sensitivity improve after the transmission distances studied as seen in the green curve of Fig. 3a. When doing a linear regression of the points at several SMF lengths, the coefficient of determination (R^2) is around 0.99, indicating there is very good correlation between both variables. Still, we consider that by properly optimizing the APD gain, the correlation could be improved. Furthermore, both DML and EML results lie basically along the same line. This shows that TDEC can predict the Rx sensitivity (as it drives the Tx OMA requirement) which is of high importance for interoperability.

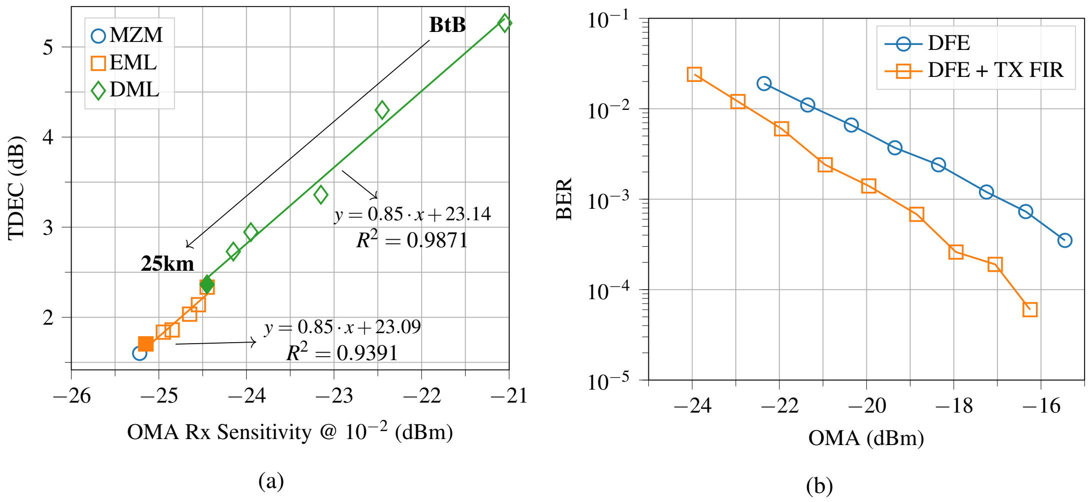


Fig. 3: (a) TDEC vs Rx sensitivity with DFE equalization at different fiber lengths for DML and EML as Tx. Solid line is the linear regression. Solid markers show results after 25 km. (b) BER vs. ROP with and without pre-emphasis for a DML Tx.

The EML also operates in the negative CD regime, but its chirp and total accumulated CD (after 25 km is -36 ps/nm) are lower than the DML: consequently, the TDEC and Rx sensitivity improve only slightly after transmission. Yet, the R^2 value when making a linear regression of the TDEC against Rx sensitivity after several SMF lengths is almost 0.94, confirming the correlation between the two parameters.

The highest TDEC and worst sensitivity for the DML corresponds to BtB, which we believe is limited by the electrical connections of the packaging. In order to improve the performance, either a more complex equalizer can be used at the Rx or a higher OMA Tx can be launched. Alternatively, to improve TDEC, the Tx should be enhanced. In order to test this latter option, we add an analog FIR filter with 6-taps spaced 7.5 ps as pre-emphasis in the Tx whose coefficients were optimized offline by compensating the BW.

Fig. 3b shows the BER against OMA with and without the pre-emphasis FIR filter. At BER=10^{-2}, the Rx sensitivity improves by 1.5 dB to -22.8 dBm, whereas the measured TDEC reduces commensurately to 3.8 dB. Hence, TDEC again faithfully predicts the DML performance. In addition, from the Rx sensitivity achieved with the pre-equalized DML (P_{out}=+6.2 dBm), a power budget of 29dB can be realized. After fiber transmission, the Rx sensitivity is further improved and the link budget is assured. We expect that with better electrical connections in the TOSA, more margin could be added to the link.

4. Conclusions

We experimentally evaluate the validity of the TDEC in negative dispersion regime, as it may happen in 50G-PON US. After testing both 25G DML and EML, we show that TDEC penalty linearly correlates with Rx sensitivity at several SMF lengths. These results show the effectiveness of the recently agreed TDEC metric for 50G US in assessing different 25G-class Tx candidates. Moreover, with a pre-equalized 25G DML, N1 power budget class can be achieved in BtB and after negative CD transmission.

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