Upstream Dispersion Management of 25-Gb/s Duobinary and PAM-4 Signals to Support 0-40km Differential Reach

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25-Gb/s per wavelength capacity is extensively discussed in both IEEE and ITU-T standardization to support the increasing bandwidth requirement. In this letter, we propose to use optical dispersion compensation technique in optical line terminal (OLT) combined with bandwidth-limited electro-absorption modulated laser (EML) in optical network unit (ONU) to achieve 25-Gb/s capacity for the upstream link. We evaluate the positive and negative dispersion tolerance of 25-Gb/s electrical duo-binary (EDB) and PAM-4 signals. 39.5-dB and 31-dB upstream loss budget for 25-Gb/s EDB and PAM-4 signals have been achieved by using -600ps/nm and -500ps/nm optical dispersion compensation in OLT respectively, both supporting 0-40km differential reach.

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As the bandwidth demand of emerging high quality's multimedia applications keeps increasing, it is essential to developing next-generation passive optical network beyond 10-Gb/s to satisfy the end user's bandwidth demand in the near future. 25-Gb/s per wavelength has been considered as the next generation access technologies to support 100-Gb/s capacity for both ITU-T and IEEE. Various solutions have been proposed to realize 100-Gb/s PON systems by using high-order modulation formats such as quaternary level pulse amplitude modulation (PAM-4)[1-3], electrical duo-binary (EDB) [4-6] and optical duo-binary (ODB)[7]. Non-return-to-zero (NRZ) has also been proposed as the downstream modulation format option [8,9], but after the bandwidth-limited receiver in optical network unit (ONU), it is still EDB format and only the detection algorithms are different, therefore we still consider this NRZ format as a variant of EDB. And ODB modulation schemes is beneficial to the fiber transmission as a result of the chromatic dispersion (CD) tolerance characteristic. But a high bandwidth Mach-Zehnder Modulator (MZM) and the equal bandwidth receiver with the data rate are required, which increase the expenditure cost and limits its use in the OLT. Until now the modulation format options have not been finalized yet, but most of the researches are focused on downstream directions. For 25-Gb/s data rate in upstream direction, ODB should be out of the choice due to its high cost in ONU, therefore EDB or PAM-4 will be the options based on 10G-class devices. Since C-band is also a choice for upstream wavelength, dispersion compensation is required to support 0-40km differential reach. Burst-mode electrical dispersion compensation (BM-EDC) has been proposed to compensate 0-40km differential reach [10], and we have proposed to use optical dispersion compensation (ODC) in optical line terminal (OLT) to compensate 0-100km differential reach [11], both for upstream 10-Gb/s directly-modulated signals. However, there have been no demonstrations on the dispersion compensation to support 0-40km differential reach which means supporting all the users distributed within 40km for 25-Gb/s upstream signals. In paper [2], the reach is doubled from 20km to 40km by using -340ps/nm dispersion compensation fiber (DCF) at the OLT side for the downstream. But it is not the optimal dispersion compensation value for the users of 0-40km.

In this paper, we employ ODC in OLT to compensate the chromatic dispersion of 0-40km differential reach of both 25-Gb/s EDB and PAM-4 signals. We evaluate the dispersion tolerance of the 25-Gb/s EDB and PAM-4 signals on both positive and negative dispersion values in order to find the optimal dispersion value in OLT, and compare the upstream loss budget for the two modulation formats at its optimal dispersion compensation value. Finally, we achieved 39.5-dB and 31-dB loss budget for EDB and PAM-4 formats at -600ps/nm and -500ps/nm dispersion at OLT, respectively. Considering the facts that burst-mode duobinary receiver has already been available [2] and ODC can support multiple channels, we conclude electro-modulation laser (EML) based EDB format with ODC in OLT would be a good candidate for the upstream in symmetric 100G-PON in C-band. Note that 39.5-dB upstream loss budget is also the record value for 25-Gb/s time-division-multiplexed PON (TDM-PON).

As for the downstream solution of 100G-PON, we have demonstrated the first field trial of a real-time 100-Gb/s TWDM-PON system with 4×25-Gb/s downstream and 4×10-Gb/s upstream transmission using 10G-class DMLs and APD/PIN receivers with power budget of 33 dB after 40-km SMF transmission [12]. So in this paper, we only discuss the upstream solution of 100G-PON. Since both PAM-4 and EDB formats can relax the bandwidth requirement of the

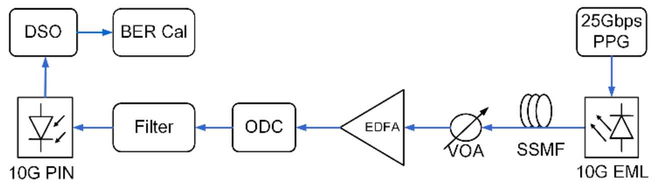

Fig. 1: Experimental setup

transceivers [13], 10G-class transmitter and receiver are used in the experiment. Fig. 1 depicts the experimental setup. Commercially available 10G-class electro-absorption modulated laser (EML) are used as 25-Gb/s upstream transmitter in ONU. The data sequence is generated by pulse pattern generator (PPG, Keysight N4960A).

For 25-Gb/s PAM-4 format generation, two channels of 12.5-Gb/s data are used followed by a PAM-4 encoder and one channel is delayed by two PRBS signals. At the OLT, we use an erbium-doped fiber amplifier (EDFA) to pre-amplify the upstream signal and then use an optical dispersion compensator (ODC) with dispersion tunability (II-VI Photonics PS3400) to compensate the fiber dispersion from the differential reach. The group delay and calculated dispersion curves of the used ODC is shown in [10], which is the same device used in this paper. We also use an optical filter with 4-nm bandwidth to suppress amplified spontaneous emission (ASE) power from the EDFA, which can be replaced by a DEMUX in symmetric 100G-PON systems. Then we use a 10G-class PIN (Conquer-KG-PR-10G) to detect the 25-Gb/s upstream signal. Due to lack of real-time bit-error-rate tester (BERT) for EDB and PAM-4 formats, we use a digital storage oscilloscope (DSO) to capture the electrical signal and calculate the bit-error-rate (BER) in Matlab. To simplify the calculation, the word length of the pseudo-random bit sequence (PRBS) data is set at 2^{12}-1. Note that no any digital signal processing (DSP) algorithms are used to mitigate the system interference. The frequency response of combined of EML and PIN at optical back-to-back (BtB) is shown in Fig. 2. It is noted that the 3-dB and 20-dB bandwidth of the system at BtB case are about 8GHz and 14GHz, respectively. Therefore, the system is more suitable for EDB and PAM-4 modulation formats to support 25-Gbps per wavelength TDM-PON.

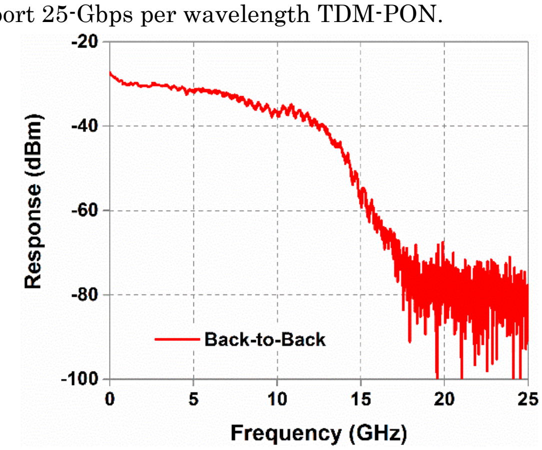

Fig. 2: Frequency response of 10G-class EML and PIN at Back-to-Back.

We conduct an experiment to investigate our proposed system architecture as shown in Fig.1. Consideration of the wavelength drift of the EMLs in the ONU side caused by the burst mode, we use a 4-nm bandpass filter to suppress the ASE power from the EDFA. So 5-dB improvement of receiver sensitivity is achieved as shown in Fig. 3. So a 4-nm optical filter is always used at the following experiments. The BER for 10-Gb/s data rate is also measured for reference. Compared to the transmission of 10-Gb/s data rate, the PAM-4 is worse more than 10 dB which is caused by the requirement of device's linearity for PAM-4 and limits the signal's extinction ratio. Then, we evaluate the dispersion tolerance of 25-Gb/s PAM-4 signal on both positive and negative dispersion values at BtB case as shown in Fig. 4. Obviously the PAM-4 signal has much stronger tolerance on negative dispersion attributed to the positive chirp of the EML. But with the positive dispersion, the sensitivity of the PAM-4 is gradually worse than BtB case. If the positive dispersion is more than 500ps/nm, the BER performance cannot reach the sensitivity of 1×10^{-3}. So PAM-4 is more sensitive with the positive dispersion of fiber transmission. The BtB sensitivity (defined at the BER of 1×10^{-3}) variations with different dispersion is shown in Fig. 5.

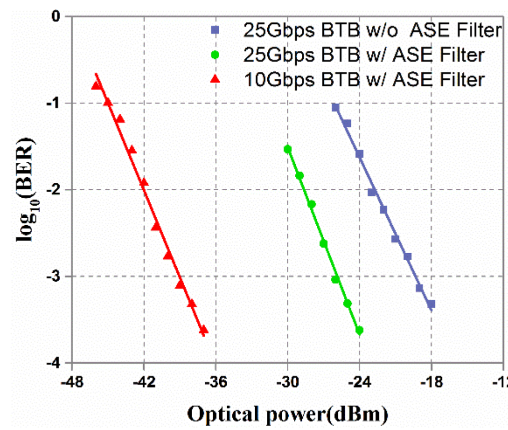

Fig. 3: Receiver performance of 25-Gbps PAM-4 with and without ASE filter and 10-Gbps NRZ with ASE filter

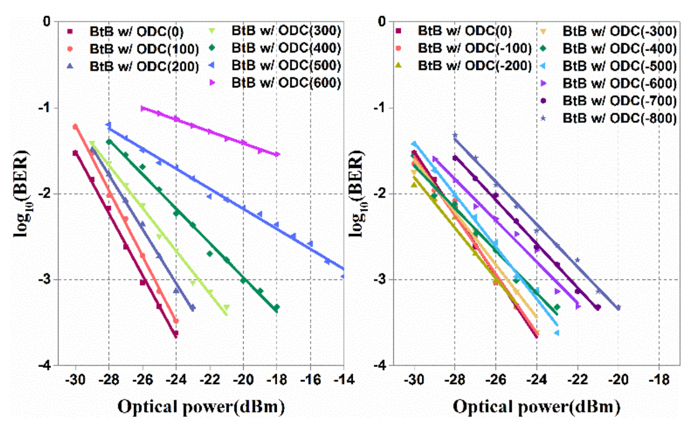

Fig. 4: Upstream 25-Gb/s PAM-4 signal BER measurement with different positive (left) and negative (right) dispersion values at the BtB case.

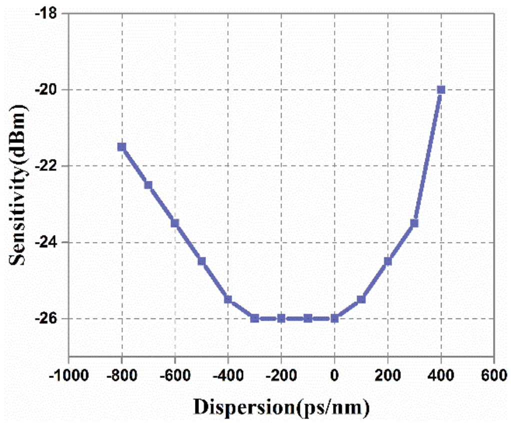

Fig. 5: Upstream 25-Gb/s PAM-4 signal BtB sensitivity variations with dispersion.

With the positive dispersion increase from 0 to 600ps/nm, the sensitivity is severely degraded and even 3.8×10^{-3} BER cannot be achieved when the dispersion is higher than 500ps/nm. But with negative dispersion from 0 to -800ps/nm, we find the sensitivity varies in a small range between -26dBm to -21.5dBm. We discover that PAM-4 is more tolerance with negative dispersion but is sensitive with positive dispersion. For the dispersion values between 0 and -300ps/nm, the sensitivity keeps unchanged. Consider both the positive and negative dispersion tolerance of the 25-Gb/s PAM-4 signal to support 0-40km differential reach, we decide to set the optimal dispersion value at -500ps/nm in OLT. Therefore, the residual dispersion values at 0, 20km and 40km reaches are -500ps/nm, -160ps/nm and 180ps/nm respectively. For all the cases, the sensitivities keep at good values. The eye diagrams of 25-Gb/s PAM-4 signal with and without -500ps/nm ODC in BtB, 20km and 40km fiber transmission cases are shown in Fig. 6. The eyes are significantly degraded after 20km and 40km fiber transmission without ODC, however the eyes are clearly open for all the cases with ODC, proving the feasibility of using fixed ODC in OLT to compensate the dispersion from the differential reaches. Then we calculate the BER of 25-Gb/s PAM-4 signal for the different cases in Fig. 6, and the results are shown in Fig. 7. At all the reach cases, the sensitivity is around -25 dBm and no significantly transmission penalty is observed. Considering the EML output optical power of 6dBm, a total 31-dB loss budget is achieved.

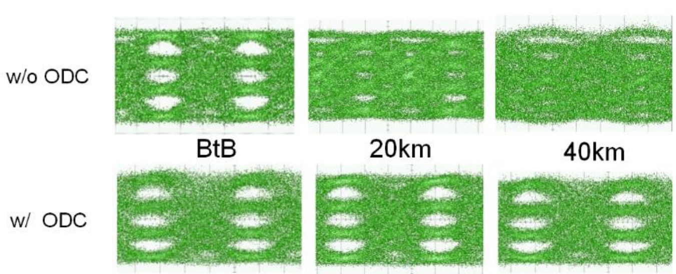

Fig. 6: Eye diagrams of 25-Gb/s PAM-4 signal with and without -500ps/nm dispersion compensation in BtB, 20km and 40km fiber transmission cases.

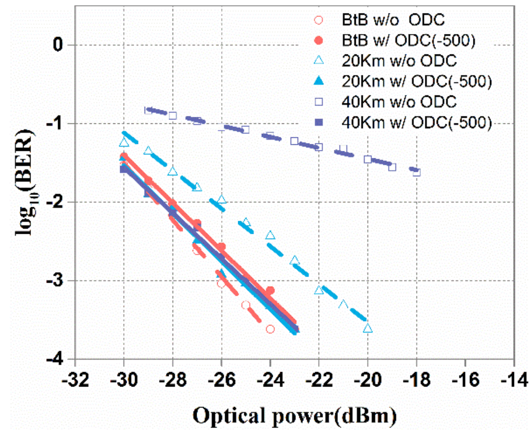

Fig. 7: BER curves of 25-Gbps PAM-4 signal in BtB, 20km, 40km fiber transmission case.

Then we evaluate the dispersion tolerance of 25-Gb/s EDB signal. Similar with the PAM-4 case, we also place a same ASE filter at the OLT side to suppress the EDFA noise. It is noted that the receiver sensitivity is improved about 2 dB as shown in Fig. 8. So an ASE filter is also used at the following evaluation. We evaluate the dispersion tolerance of 25-Gb/s EDB signal on both positive and negative dispersion values in the BtB case as shown in Fig. 9. To make the fair comparison with the PAM-4 case, the dispersion value is also tuned from -800ps/nm to 600ps/nm. Similar with the PAM-4 signal, the 25-Gb/s EDB signal also has much stronger tolerance on negative dispersion. 3.8×10^{-3} BER cannot be achieved when the dispersion is higher than 400ps/nm and for the dispersion between 0 to -700ps/nm, the sensitivity variation is within 4 dB. The BtB sensitivity as a function of the dispersion value for 25-Gb/s EDB signal is shown in Fig. 10, where the variation trend is similar with the PAM-4 case. However, the sensitivity is ~7dB better than the PAM-4 case since the EDB format has only 3 levels and is more tolerant to the noise compared with the 4-level PAM-4 signal. Consider both the positive and negative dispersion tolerance of the 25-Gb/s EDB signal to support 0-40km differential reach, we set the optimal dispersion at -600ps/nm in OLT. The eye diagrams of 25-Gb/s EDB signal with and without -600ps/nm ODC in BtB, 20km and 40km fiber transmission cases are shown in Fig. 11, and the corresponding BER results are shown in Fig. 12. The sensitivity in the BtB case with ODC is the worst compared with 20km and 40 km fiber transmission cases, however the target is to achieve the best sensitivity at the longest distance due to the highest transmission loss and the transmission dispersion penalty is within 2 dB. At 40 km reach, the sensitivity is around -32 dBm, same with the 20 km reach case. Considering the EML output optical power of 7.5 dBm, a total 39.5-dB loss budget is achieved, which is the record value for 25-Gb/s TDM-PON and would be a good candidate for 100-Gb/s PON. Note that the output power of EML is higher for the EDB format since it has lower linearity requirement on the transmitter compared with the PAM-4 format therefore the EML can be biased at higher current [14].

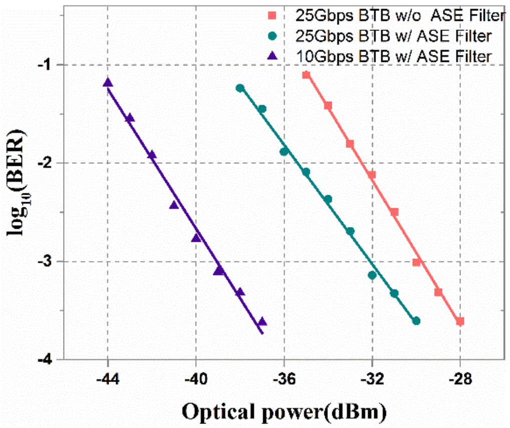

Fig. 8: Receiver performance of 25-Gbps EDB signal with and without ASE filter and 10-Gbps NRZ with ASE filter

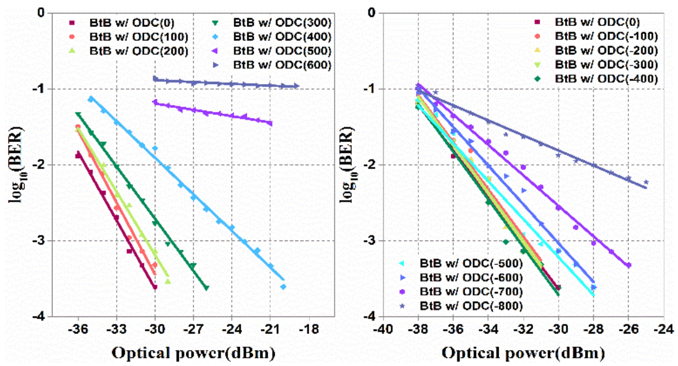

Fig. 9: Upstream 25-Gb/s EDB signal BER measurement with different positive (left) and negative (right) dispersion values in the BtB case.

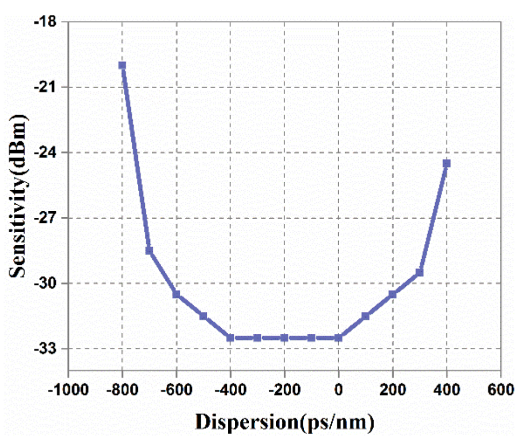

Fig. 10: Upstream 25-Gb/s EDB signal BtB sensitivity variations with dispersion.

As for the two upstream schemes, 39.5-dB and 31-dB loss budget for 25-Gb/s EDB and PAM-4 signals have been achieved respectively and both are supporting 0-40km differential reach. So the EDB performance is better than the PAM-4. The main advantages of EDB and PAM-4 schemes are that the system bandwidth requirement is relaxed and both of them are more CD tolerance compared with the NRZ format. So we can use relatively low bandwidth optical devices to support high speed

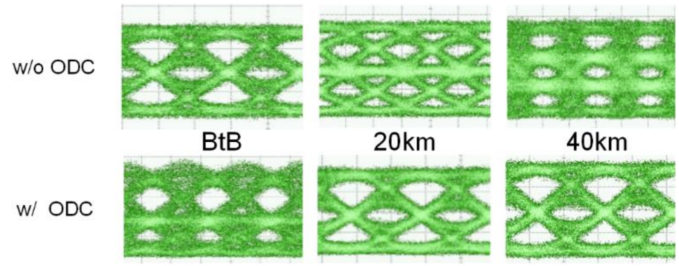

Fig. 11: Eye diagrams of 25-Gb/s EDB signal with and without -600ps/nm dispersion compensation in BtB, 20km and 40km fiber transmission cases.

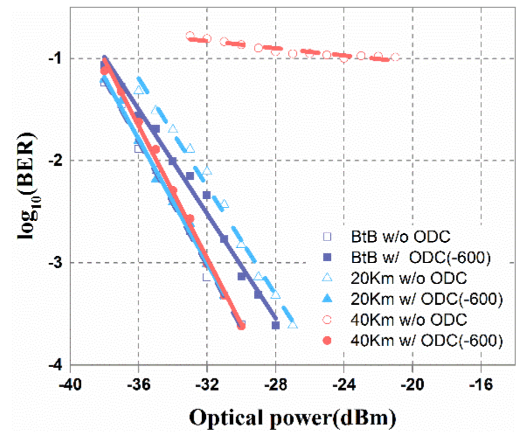

Fig. 12: BER curves of 25-Gb/s EDB signal in BtB, 20km, 40km fiber transmission case.

transmission. PAM-4 format requires linear transceiver which limits the optical signal extinction ratio and is more challenging for the upstream burst-mode (BM) receiver [15]. As for the EDB format, only the demodulation may need high speed duobinary-to-binary conversion circuit which may increase the system cost. But the increased cost in OLT can be shared by all users. So the EDB format using 10G-class EML and PIN for the upstream would be a better solution. Figure. 13 shows the burst-mode timing sequences of upstream. We assume a preamble which accommodates laser turn-on and residual burst settling effects.

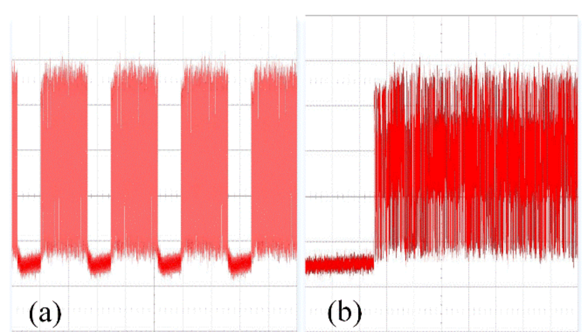

Fig. 13: Upstream burst-mode timing sequences at 100ns/div (a) and 100ns/div (b).

In conclusion, we propose to use an optical dispersion compensator with negative dispersion in OLT to support 0-40 km differential reach for 25-Gb/s upstream signals. The optimal dispersion value is evaluated for both PAM-4 and EDB formats to achieve the highest loss budget and the lowest transmission dispersion penalty. The maximal loss budget of 39.5 dB can be achieved for EDB format, which is the record value for 25-Gb/s TDM-PON. Besides, the ODC can support multi-channel operations. Therefore, EML based EDB format in ONU combined with ODC in OLT will be an attractive solution for the upstream direction in symmetric 100G-PONs.

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