Demonstration of 50Gb/s/λ Symmetric PAM4 TDM-PON with 10G-class Optics and DSP-free ONUs in the O-band

Kuo Zhang[1,2], Qunbi Zhuge[2,3], Haiyun Xin[1], Zhenping Xing[2], Meng Xiang[2], Sujie Fan[2], Lilin Yi[1,*], Weisheng Hu[1] and David V. Plant[2]

[1]*State Key Lab of Advanced Optical Communication System and Networks, Shanghai Jiao Tong University, Shanghai, 200240, China*
[2]*Department of Electrical and Computer Engineering, McGill University, Montreal, QC, H3A 2A7, Canada*
[3]*Ciena Corporation, Ottawa, Ontario, K2K 0L1, Canada*
[*]*Email: lilinyi@sjtu.edu.cn*

Abstract: We demonstrate a 50Gb/s/λ PAM4 TDM-PON based on 10G-class DMLs and PDs in O-band with downlink pre-compensation and uplink post-equalization. Results show that, without any DSP in the ONU, 29dB optical power budget is achieved.

OCIS codes: (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems.

1. Introduction

In recent years, the ITU-T and IEEE have witnessed the progress of passive optical network (PON) standards from 10Gb/s/λ to 25Gb/s/λ. Meanwhile, driven by the increasing user bandwidth demand such as high-definition video and 5G mobile front-haul applications, PON systems with higher capacity are being developed. For PON systems beyond 25Gb/s/λ, 10G-class optics are also desired in order to reuse the existing devices and minimize the deployment cost [1]. But due to the bandwidth limitation of 10G optics, digital signal processing (DSP) is an attractive approach to mitigate the distortions in these systems. Hence recently, the DSP technology has been widely adopted in the high capacity PON systems [2]. However, DSP relies on high-speed digital-to-analog or analog-to-digital converters (DAC/ADC), which are not cost-effective especially for the optical network units (ONUs) located at the user side. For example, the 50Gb/s PAM4 PON requires ADCs with a sampling rate > 25GS/s at the ONU side. Therefore, high capacity PON systems with both DSP-free ONUs and 10G-class optics will be of great interest to the development of future cost-effective optical access networks.

The centralized DSP concept in which all the DSPs are put at the optical line terminal (OLT) side has the potential to reduce the complexity of ONUs or enable DSP-free ONUs, and thus greatly lower the cost of PON systems. In [3] 25Gb/s PAM4 TDM-PON is realized with this concept based on 10G-class optics, and in [4] 64Gb/s PAM4 TDM-PON is realized for downlink with a 5-tap equalizer DSP in the ONU. However, these demonstrations are working in the C-band transmission window, in which one critical issue exists when the pre-compensation DSP for downlink is applied. In particular, different ONUs in a TDM-PON have different distances from the OLT and experience different impairments due to the chromatic dispersion (CD). Each downlink frame with a pre-compensation DSP can only serve a small range of ONUs. Therefore, the broadcasting frames (such as the PCBd [5]) in TDM-PON that are intended for all the ONUs could not be correctly received by all ONUs. In contrast to the C-band transmission window, the O-band wavelengths have nearly zero CD. The transmission performance is only degraded by the device bandwidth and a small portion of nonlinearity. Different ONUs with different distances from the OLT have almost the same physical impairment. In addition, the IEEE is currently working on the standardization of NG-EPON in the O-band. Therefore, it would be a good option to implement DSP-free ONUs in the O-band by centralizing all the DSPs in the OLT, while guaranteeing that the broadcasting frames can be correctly received by all ONUs.

In this paper, we experimentally demonstrate a 50Gb/s/λ PAM4 TDM-PON with DSP-free ONUs based on 10G-class directly modulated lasers (DMLs) and PDs in the O-band enabled by downlink pre-compensation and uplink post-equalization. In particular, we apply raised cosine (RC) pulse shaping and pre-emphasis in the downlink transmitter side with a DAC, and feedforward equalization (FFE) in the uplink receiver side. Parametric investigations on the pre-compensation and post-equalization, including the roll off factor of RC shaping and the number of filter taps, are also conducted. Results show that, without any DSP in the ONU side, 29dB power budget is achieved over transmission distances from 0 to 20km with SOA-TOF-PIN and DML. To the best of our knowledge, this is the first demonstration of PON systems in the 50Gb/s/λ paradigm based on 10G Optics without any DSP in the ONU.

2. Experimental setup

Fig. 1 shows the experimental setup of the proposed 50Gb/s/λ PON system. For the downlink, a low-cost commercial available DML (Xeston technologies) operating at a 1312nm wavelength is used at the transmitter. The output power is 10dBm high thanks to the DML's exclusion of external modulators. The electrical signal is generated from a DAC with a sampling rate of 70GS/s and amplified to ~2.5 Volts peak-to-peak by an RF driver. After fiber transmission,

978-1-943580-38-5 © 2018 Optical Society of America

the signal is first attenuated by a variable optical attenuator (VOA) which emulates the power splitter in PON systems, then detected by a receiver which is comprised of a semiconductor optical amplifier (SOA) (Thorlabs BOA1132, a polarization controller is also placed due to its polarization sensitivity but can be removed with other SOAs), a tunable optical filter (TOF) (Agiltron Inc., 1nm bandwidth) and a PIN-TIA (Discovery DSC-R402). Finally, the detected electrical signal is captured by a real-time oscilloscope (RTO) with a sampling rate of 80GS/s for offline BER calculation. The uplink setup is exactly the same with the downlink except that the electrical signal is generated by combining two bit pattern generators (BPGs) (SHF12104) rather than from a DAC, because DSP is not needed at the transmitter and only conducted at the receiver after RTO for uplink. In the experiment, the bandwidth of the DML is 17GHz @3dB, the bandwidth of the PIN-TIA is 10GHz @3dB and 12GHz @6dB, and the end-to-end bandwidth of the whole system is ~9GHz as shown in Fig. 1(c).

In the proposed PON system, both DSPs in the downlink and uplink are centralized in the OLT. For the downlink, the DSP is only at the transmitter side and is mainly comprised of four procedures: (i) the raw data sequence is Grey-coded and mapped to PAM4 symbols; (ii) a digital RC pulse shaping filter at 2 samples per symbol (sps) is applied to the PAM4 symbols in order to not only minimize the inter-symbol interference induced by limited device bandwidth, but also help avoid aliasing and respect the Nyquist sampling theorem when the DAC sampling rate is not enough; (iii) the digital signal after pulse shaping is resampled to match the DAC sampling rate which is 70GS/s in this work; (iv) the resulting digital waveform is pre-emphasized using a finite-impulse response (FIR) filter. The FIR filter is designed to compensate for the frequency response of the entire chain of components along the link including the DAC, RF driver, DML, and the receiver-side PIN-TIA. The tap coefficients are determined with a least mean square (LMS)-based algorithm, and the same coefficients are applied for all ONUs. For the uplink, the DSP is only at the receiver side including: (i) the captured data from the RTO is first down-sampled to 2sps; (ii) a linear FFE operated at 2sps is adopted; (iii) the digital waveform is down-sampled to 1sps for symbol decision and error counting.

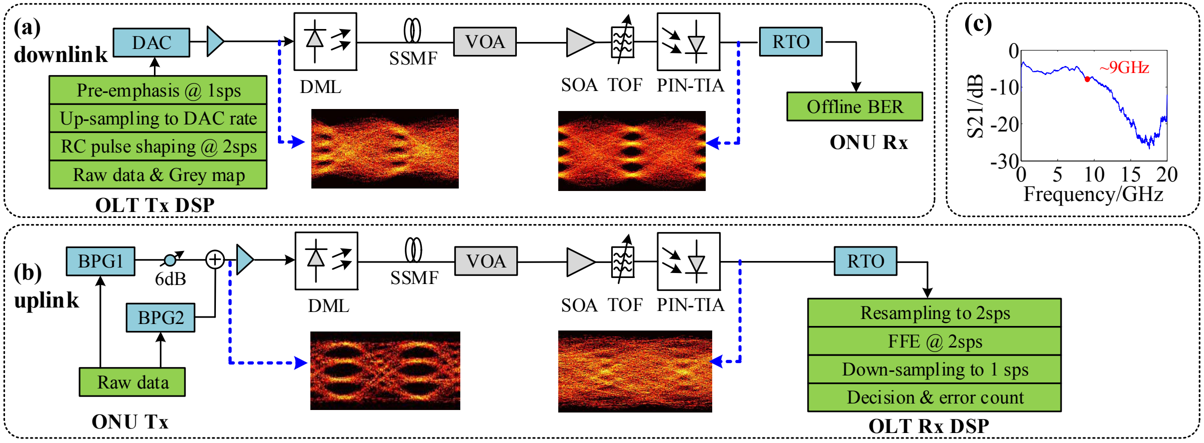

Fig. 1. Experimental setup for (a) downlink, and (b) uplink. (c) The frequency response of DML and PIN-TIA.

3. Results and discussions

First, to illustrate the process of the downlink pre-compensation and uplink post-equalization, eye diagrams are depicted in the inset of Fig. 1. For the downlink, it is shown that the RF signal output from the DAC is severely distorted due to the pre-compensation FIR DSP. After the DML, fiber link and the PIN-TIA, the eye diagram becomes quite open and clear. In contrast, for the uplink the RF signal after the BPGs is open and clear, but after the whole chain of optics the eye diagram is severely distorted.

Next, the BER versus received optical power (ROP) is plotted in Fig. 1(a) and (b). For the downlink, the roll off factor α is set to 0.35 and the tap number of the pre-emphasis FIR filter is set to 75. The optical sensitivity at the HD-FEC (3.8×10^{-3}) is shown to be -19dBm, resulting in 29dB optical power budget considering the 10dBm DML output power. It is also observed that, although tap coefficients are obtained in the BtB case as aforementioned, the performances of the BtB case and 20km case show almost no difference thanks to the zero dispersion in the O-band. This implies that a broadcasting frame can be correctly received by all ONUs. For the uplink, the tap number of the post-FFE is set to 35. Though the DSPs for the downlink and uplink are located at the transmitter and receiver side, respectively, negligible optical sensitivity difference is observed for the two scenarios. Also, the BER performance of the systems with and without SOA pre-amplification is depicted and compared, in which a ~6dB power budget improvement is achieved by the SOA for both the uplink and downlink.

Then, we study the required tap number in the pre-emphasis filter and the post-FFE in Fig. 2(c). For the downlink pre-emphasis filter, it is shown that the BER performance reaches an error floor when the tap number is more than 55, while for the uplink post-FFE, it is shown that the BER performance reaches an error floor when the tap number is more than 31. In the system, both the responses of the pre-emphasis filter and post-FFE are exactly the inverse of the whole system's response. The difference of the required tap number between them can be explained from two aspects: (i) the pre-emphasis is operated at 1sps @ 70GS/s rate corresponding to 2.8sps @ 25G baud rate, whereas the post-FFE is operated at 2sps; and (ii) the BPG used for the uplink has a much higher bandwidth than the DAC for the downlink.

Finally, we investigate the impact of pulse shaping roll off factor of the pre-emphasis filter for the downlink. The roll off factor is a parameter which can relax the requirement of device bandwidth and decrease the sampling rate of the DAC by reducing the bandwidth of the electrical signals. In particular, a RC filter with a roll off of α can limit the bandwidth to $(1 + \alpha) \times bandrate/2$ and thus decrease the DAC sampling rate to $(1 + \alpha) \times bandrate$ according to Nyquist sampling theorem. Hence, this factor is very important in consideration of a deployment cost. As shown in Fig. 2(d), the α that gives the best performance is 0.35. When such a roll off factor is applied, the required DAC sampling rate can be $(1 + 0.35) \times 25 = 33.75$GS/s, in other words, the 70GS/s DAC adopted in the experiment can be replaced by a 33.75GS/s one with a lower cost.

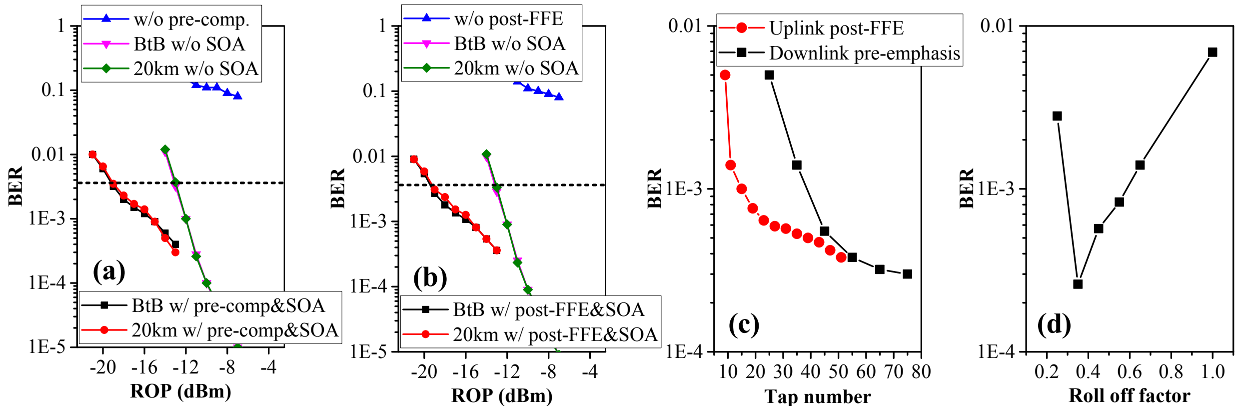

Fig. 2. (a) Downlink BER performance; (b) Uplink BER performance; (c) BER versus downlink/uplink filter tap number; (d) BER versus downlink pulse shaping roll off factor.

Regarding the practical implementation of the demonstrated system, the following facts need to be considered: (i) in the deployments of TDM-PON systems, the burst mode operation in uplink is necessary, which will induce optical power budget penalty compared with the continuous mode; (ii) in the ONU, we adopt SOA for pre-amplification because it is possible to be integrated with the PD, and the TOF in the setup can be replaced by a compact thin film filter. Besides, single APD with higher sensitivity can also be used to replace the SOA-TOF-PIN; (iii) since the OLT and ONU are located at different sites, tap coefficients of the pre-emphasis filter could not be adaptively trained, but can be fixed in memory if the system's response is afore-known. In this case, the frequency response difference among different ONU receivers needs to be considered in future works.

4. Conclusions

In this work, we have demonstrated a 50Gb/s/λ symmetric PAM4 TDM-PON with DSP-free ONUs in the O-band based on 10G-class optics, assisted by downlink pre-compensation and uplink post-equalization. Experimental results show that 29dB optical power budget is achieved with a DML and an SOA pre-amplified receiver. We also show that a 55-tap pre-emphasis filter and 31-tap post-FFE are sufficient to achieve good performance, and the optimal RC roll off factor is 0.35 which implies that the 70GS/s DAC adopted in the experiment can be replaced by a 33.75GS/s one.
Funding: NSFC (61431009, 61371082, 61521062), National Science and Technology Major Project of the Ministry of Science and Technology of China (2015ZX03001021), China Scholarship Council (201606230160).

5. References

[1] L. Xue et al., OFC2017, Paper M3H.1.
[2] S. Yin et al., J. Lightwave Technology, vol. 35, no. 4 (2017).
[3] C. Ye et al., ACP2016, Paper AF1C.6.
[4] J. Zhang et al., ECOC2017, Paper P2.SC8.53.
[5] ITU-T G.989 specifications.