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Design and analysis of high-speed optical access networks in the O-band with DSP-free ONUs and low-bandwidth optics

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Abstract: In this paper, we demonstrate and investigate high-speed passive optical networks (PON) in the O-band without using any digital signal processing (DSP) at the ONU side, meanwhile still adopting cost-effective low-bandwidth optics. We show that with commercial 10G-class optics including DML and PIN-TIA, 50Gb/s PAM4 PON with a power budget up to 29dB is achieved under the HD-FEC BER limit. We present the detailed design procedure of the DSP including the downlink Nyquist pulse shaping and pre-equalization and uplink post-equalization, and conduct a comprehensive study on this system including DSP complexity, DAC/ADC sampling rate requirement and tolerance to the response diversity of ONU receivers. We conclude that, 1) 55 and 35 taps are sufficient for downlink and uplink digital filters to approach the BER floor; 2) the minimum required DAC and ADC sampling rate are respectively 33.75GS/s and 32GS/s to achieve the optimal performance; and 3) with 1dB sensitivity penalty at the HD-FEC BER limit, the allowable response diversity of ONU receivers can be from −2.2dB/10GHz to 1.8dB/10GHz. Furthermore, we explore and demonstrate the suitable data rate based on on-off keying and duobinary modulation formats in this system and present corresponding results.

1. Introduction

During the past few years we have witnessed the progress of passive optical network (PON) standards from 10Gb/s to 25Gb/s per wavelength by ITU-T and IEEE [1,2]. Meanwhile, in anticipation of growing bandwidth demand due to emerging new applications such as fixed-mobile convergence, 5G, 4K/8K TV, online gaming, etc [3–5], PON systems with higher capacity are being developed [6,7]. In early 2018, a proposal of 50Gb/s per wavelength PON has been made by ITU-T Study Group 15 [8]. For PON systems beyond 25Gb/s per wavelength, the adoption of low-bandwidth optics is still a desirable choice in order to reuse legacy components and sustain low-cost deployments [9–24]. In such bandwidth-limited systems, digital signal processing (DSP) is necessary to avoid performance degradation. Hence DSP has been widely studied in high-speed PON systems recently [25–27]. However, DSP relies on high-speed digital-to-analog or analog-to-digital converters (DAC/ADCs) and numerical operations, which are not cost- or power- efficient. For example, the 50Gb/s 4-level pulse amplitude modulation (PAM4) PON generally requires DAC/ADC with a sampling rate of 25~50GS/s at the ONU side. This fact is even more serious for optical network units (ONUs) at the user side due to its large scale of deployments. Therefore, high-speed PON systems with both DSP-free ONUs and low-bandwidth optics will be of great significance for the progress of future cost-effective optical access networks.

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In most previous demonstrations of DSP-based optical access networks, the cost asymmetry between ONU and optical line terminal (OLT) was not fully considered. In these demonstrations, DSPs were implemented either at the receiver side [10–15] or at both the transmitter and receiver sides [16–22]. As a result, DSP is always needed in the multipoint ONU, which can be a barrier for cost reduction. On the other hand, researchers in [23] and [24] have proposed to centralize the DSP in the OLT side. In this way, DSP in the ONU side can be simplified or even avoided, thereby to greatly reduce the cost and power consumption of PON systems. However, attentions on this concept have not been fully paid and detailed investigations were rarely conducted. Moreover, these two demonstrations were conducted in the C-band, which has a critical feasibility issue when the pre-compensation DSP for downlink is adopted. Specifically, since different ONUs in a TDM-PON have different reaches from the OLT, they undergo different amounts of accumulated chromatic dispersion (CD), which induces quite different impairments especially for high baud-rate transmissions. For this reason, each downlink frame with a pre-compensation DSP module can only serve a specific ONU at a certain reach from OLT. As a result, broadcasting frames such as the PCBd in TDM-PON that are intended for all the ONUs cannot be correctly received by all ONUs [28]. In contrast to the C-band transmission window, the O-band wavelengths have nearly zero CD. Different ONUs with different distances from the OLT experience almost the same physical impairment, which is mainly incurred by device bandwidth and a small portion of nonlinearity. Therefore, a common pre-compensation DSP can simultaneously accommodate all ONUs. In addition, the IEEE 802.3ca task force is also currently working on next-generation Ethernet PON (NG-EPON) in the O-band [2]. Therefore, considering all the above-mentioned facts, it would be better to implement and investigate the DSP-free ONU enabled PON system operated in the O-band with all the DSPs centralized in the OLT, which is compatible with current standardization and guarantees that broadcasting signals can be detected by all ONUs.

In this paper, we demonstrate and investigate high-speed PON systems adopting cost-effective low-bandwidth optics in the O-band without using any DSP in the ONU. In this system, all DSPs are in the OLT, which includes downlink raised cosine (RC) pulse shaping and pre-equalization, and uplink post-equalization. We show that, by using commercial low-bandwidth optics including directly modulated lasers (DMLs) and photodiodes (PDs) with only 8.5GHz end-to-end bandwidth, 50Gb/s PAM4 PON is realized with a power budget up to 29dB over distances from 0 to 20km. We present the detailed design procedure of the DSP, and conduct a comprehensive study on the system including DSP complexity, required DAC/ADC sampling rate and the impact of ONU receiver response diversity. We conclude that, 1) 55 and 35 taps are sufficient for downlink and uplink digital filters to approach the BER floor; 2) the minimum required DAC and ADC sampling rate are respectively 33.75GS/s and 32GS/s to achieve the optimal performance; and 3) with 1dB sensitivity penalty at the HD-FEC BER limit, the allowable response diversity of ONU receivers can be from −2.2dB/10GHz to 1.8dB/10GHz. Furthermore, we explore the achievable data rate of on-off keying (OOK) and duobinary modulation formats in this system. We demonstrate that the OOK format is suitable for 25Gb/s data rate with ~5dB sensitivity superiority over the 50Gb/s PAM4, whereas the duobinary format is suitable for 40Gb/s data rate with ~1dB sensitivity superiority.

Note that part of this work has been presented in [29]. The remainder of this paper is organized as follows. In Section 2, we present the experimental setup and the design of the enabling DSP. In Section 3, we show and discuss the results of the 50Gb/s per wavelength PAM4 PON system, and give detailed investigations on the system performance. In Section 4, we explore the application of OOK and duobinary formats in the system.

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2. Experimental setup and digital signal processing

2.1 Experimental setup

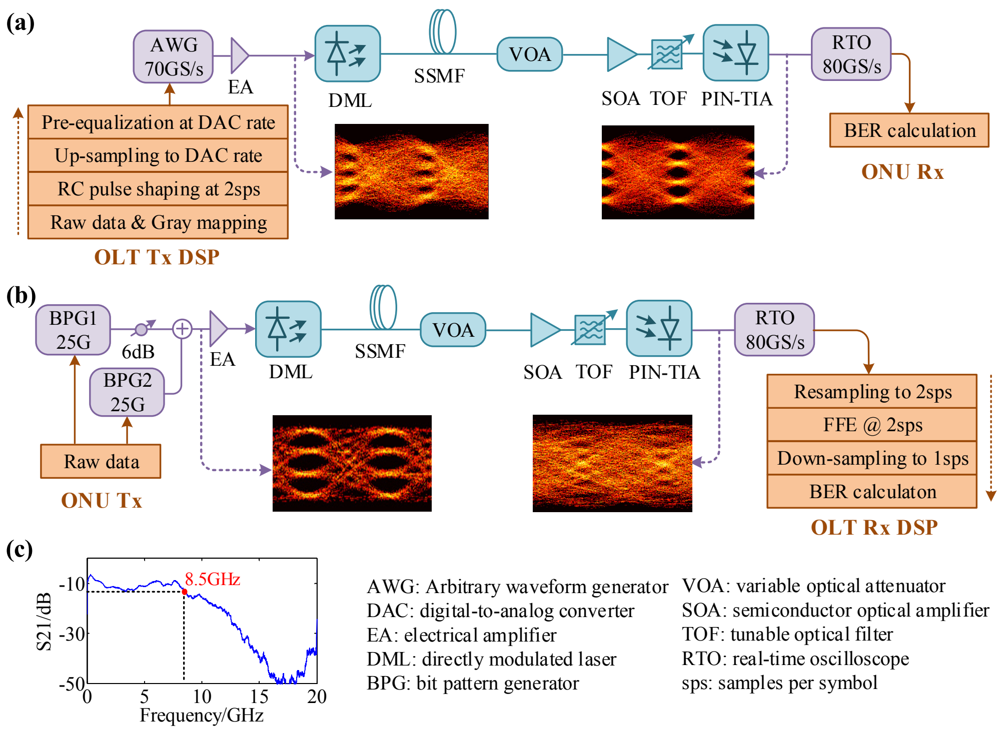

Fig. 1. Experimental setup and OLT DSP flow of (a) downlink and (b) uplink. (c) End-to-end response.

Figure 1 shows the experimental setup. For the downlink, a low-cost commercial DML operating at 1312nm wavelength is adopted at the transmitter. The output power reaches 10dBm thanks to the exclusion of external modulators. An arbitrary waveform generator (AWG) with a sampling rate of 70GS/s is adopted as a DAC to generate the electrical signal, which is then amplified to a peak-to-peak voltage (Vpp) of ~2.5 Volts by an electrical amplifier (EA). After 20km standard single mode fiber (SSMF) transmission, the signal is first attenuated by a variable optical attenuator (VOA) which emulates the power splitter in PON systems, and then detected by a receiver which is comprised of an SOA (Thorlabs BOA1132) for pre-amplification, a tunable optical filter (TOF) (Agiltron Inc., 1nm bandwidth) to suppress amplified spontaneous emission (ASE) noise, and a PIN-TIA (Discovery DSC-R402). Here, we adopt a semiconductor optical amplifier (SOA) as the optical pre-amplifier because it has the potential to be integrated. Also, the performance is similar with an avalanche photodiode (APD) [30]. Finally, the detected electrical signal is captured by a real-time oscilloscope (RTO) with a sampling rate of 80GS/s for offline BER calculation. For the uplink, the electrical signal is generated by combining two bit-pattern-generators (BPGs) (SHF12104) instead of using an AWG. This is more appropriate, because for the uplink the DSP is not needed at the transmitter and thus DAC can be avoided in a practical deployment. A 6dB electrical attenuator is placed after one BPG to halve the peak-to-peak voltage and then generate the PAM4 signals with the radio frequency (RF) combiner. The fiber link and receiver setup are exactly the same as the downlink except that all the DSP is conducted at the receiver. In the experiment, the 3dB bandwidth of the DML and PIN-TIA are respectively 17GHz and 10GHz. Consequently, the end-to-end 3dB bandwidth of the whole system is less than 8.5GHz as plotted in Fig. 1(c).

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2.2 Transmitter and receiver DSP in OLT

In this DSP-free ONU enabled PON system, both DSPs in the downlink and uplink are deployed in the OLT. The downlink DSP is at the transmitter side, which includes a pulse shaping filter at 2sps and a pre-emphasis finite impulse response (FIR) filter at the DAC sampling rate, whereas the uplink DSP is simply a feedforward equalizer (FFE) at 2sps at the receiver side. Below are the detailed descriptions of the DSP.

For the downlink, the Nyquist pulse shaping filter is essentially a filter to minimize signal bandwidth without introducing inter-symbol interference (ISI) at the decision point, in order to partially address the bandwidth-insufficiency caused by the low-bandwidth optics in PON systems. Raised cosine (RC) or root-raised cosine (RRC) filter is often adopted for the pulse shaping in transmission systems. Here, we use an RC filter, because an RRC filter needs additional matched filtering at the receiver which is not feasible in our DSP-free ONU. From the RC pulse theory, the frequency at which the power response is reduced by half is $\frac{1}{2}R_B$, and the spectral content is confined within $\frac{1}{2}R_B(1+\alpha)$, where R_B is the symbol rate and α is the roll off factor [31]. For a desired symbol rate of R_B, the roll off factor can only be within the range of $0<\alpha<min(1,\frac{DAC\,Sampling\,Rate}{R_B}-1)$ in order to avoid frequency aliasing and respect the Nyquist sampling theorem. Consequently, for 50Gb/s PAM4 ($R_B=25\text{G}$) signals, the signal bandwidth can be limited within 12.5~25GHz when α is from 0 to 1. Note that the selection of roll off factor also determines the required DAC sampling rate. In particular, when the signal bandwidth is limited within $\frac{1}{2}R_B(1+\alpha)$, the minimum required DAC sampling rate is $R_B(1+\alpha)$ according to the Nyquist sampling theorem. Figure 2 illustrates the frequency spectra and the eye diagrams when α is 1 and 0.35. It is observed that, the maximum frequency is reduced from $12.5\times(1+1)=25$ GHz to $12.5\times(1+0.35)=16.875$ GHz, while the eye diagram is not deteriorated at the decision point.

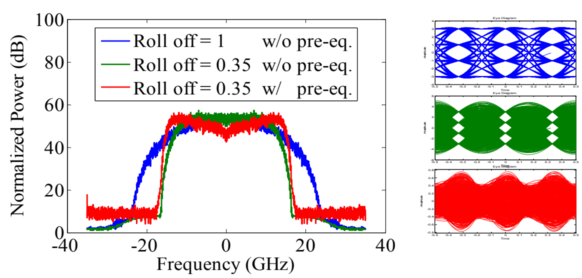

Fig. 2. Frequency spectra and eye diagrams of downlink transmitted signals

A pre-equalization filter is used after the pulse shaping. Unlike commonly used pre-equalization schemes in transmission systems that merely compensate the frequency response of transmitter-side opto-electronics, here we use this filter to equalize the response of the whole chain opto-electronics along the transmission link including AWG, EA, DML and PIN-TIA. Figure 3 shows the detailed procedure to acquire the pre-emphasis filter taps. We generated 70GBaud OOK signals at 1sps using the 70GS/s AWG (DAC), and then captured the BtB received signals after the PIN-TIA using the RTO at 160GS/s. To obtain the pre-equalization filter, least-mean-square (LMS) and muti-modulus algorithms (MMA) are often

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used. Here, we employ the LMS algorithm because the feedback error of LMS is based on the absolute signal value which can give a better performance. This LMS algorithm is operated at 1sps to obtain a set of filter coefficients. The coefficients were then transformed to the frequency domain using discrete Fourier transform (DFT), followed by the truncation of frequencies higher than $\frac{1}{2}R_B(1+\alpha)$. We do such a frequency domain truncation, because the maximum frequency of the pulse-shaped signal is $\frac{1}{2}R_B(1+\alpha)$ and the equalization of frequencies higher than $\frac{1}{2}R_B(1+\alpha)$ will lead to a dramatic reduction of the effective resolution of DAC as well as an enhanced high frequency noise. From Fig. 2, it is seen that the high frequency part after equalization is emphasized which will counteract the bandwidth-insufficiency of the PON system. The corresponding time domain signal, which is also the data loaded to the DAC, becomes quite unclear as shown in the inset eye diagram of Fig. 2. The reason that we acquire the FIR filter at the DAC sampling rate is that such a filter can accommodate any signal (with any rate, format or roll off factor) as long as the bandwidth is below $\frac{DAC\ Sampling\ Rate}{2}$, and this fact can provide a unified solution if PON systems are with flexible data rate and modulation formats. To sum up, in a practical deployment of a PON system, once we have acquired the original time domain filter, we could calculate the desired time domain filter according to the bandwidth or data rate of transmitted signals.

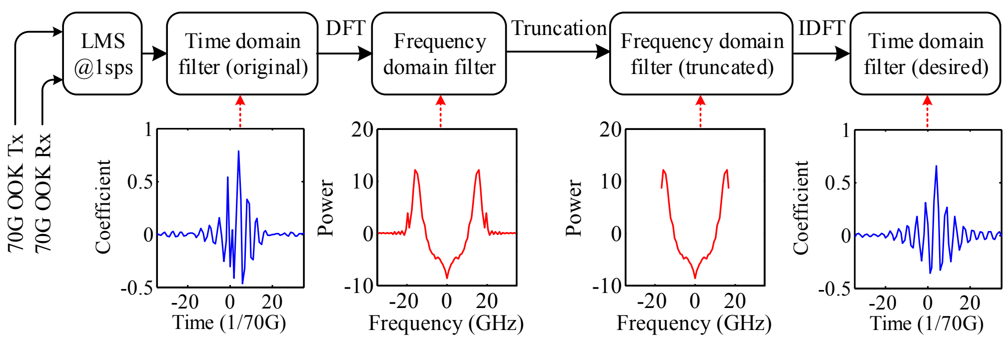

Fig. 3. Procedure to acquire the taps of the pre-equalization filter.

For uplink in the receiver-side, the signal is first resampled to 2sps followed by a linear FFE filter to compensate the distortions. This FFE filter taps are obtained adaptively at 2sps using an LMS algorithm.

3. Performances and analysis of the 50Gb/s PAM4 PON

In this section, we provide experimental results of the 50Gb/s PAM4 system. In addition to the BER and power budget results, a detailed investigation on the DSP requirements including complexity and ADC/DAC sampling rate is presented. Moreover, since we use the same pre-equalization filter for all ONUs in the downlink, the performance degradation is studied when channel responses of different ONUs are different.

3.1 BER and power budget performances

To schematically show the impact of the downlink pre-equalization and uplink post-equalization, eye diagrams have been depicted in the inset of Fig. 1. For the downlink, it is shown that the eye diagram at the output of the AWG is distorted due to the pre-equalization FIR filter. In contrast, after transmission, the eye diagram becomes quite open as expected.

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This implies that the pre-equalization filter well matches the channel response of the transmission link, and they counteract with each other after transmission, enabling a direct PAM4 demodulation without further equalization. For the uplink the eye diagram from the BPGs is open and clear. However, after transmission, it experiences severe distortions and manifests as 7-level partial response signals, which needs further equalization before PAM4 demodulation.

Then, the BER versus received optical power (ROP) is plotted in Figs. 4(a) and 4(b). For the downlink, the roll off factor α is set to 0.35 which is the optimum as shown in Section 3.2, and the tap number of the pre-equalization FIR filter is set to 75 which is sufficiently large. The optical sensitivity at the hard-decision FEC (HD-FEC) BER limit (3.8×10^{-3}) is shown to be −19dBm, resulting in 29dB power budget in view of the 10dBm DML output power, which satisfies the PR-30 power budget requirement [32]. It is also observed that, although the tap coefficients are learned in the BtB case as aforementioned in Section 2.2, the performances of the BtB case and 20km case show unnoticeable difference thanks to the extremely low CD in the O-band and the negligible fiber nonlinearity in such a short transmission distance. For the uplink, the tap number of the post-FFE is set to 35, and the optical sensitivity is shown to be −19.8dBm, which exhibits a slight optical sensitivity superiority compared with the downlink case. Also, the BER performance of the systems with and without SOA pre-amplification is depicted and compared. ~6dB power budget improvement is achieved by using the SOA for both the uplink and downlink.

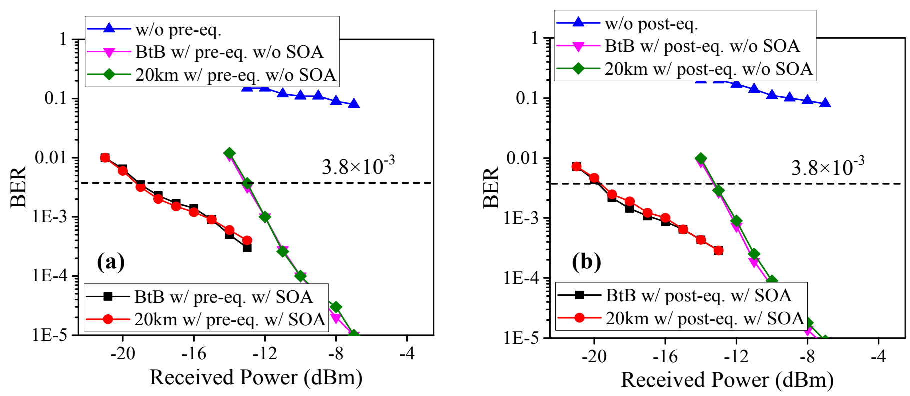

Fig. 4. BER performance versus received power of 50Gb/s PAM4 PON in (a) downlink and (b) uplink.

3.2 DSP performances

3.2.1 Optimization of the downlink pre-equalization and uplink post-equalization

In order to further reduce the complexity, we study the performance with various DSP configurations at the OLT. For the downlink, the impulse of the pre-equalization filter with different tap numbers is shown in Fig. 5(a). It is seen that most of the impulse energy is concentrated in the middle of the impulse. With these filters, the BER performance at a received power of −13dBm is plotted in Fig. 5(c), which shows that 55 taps are sufficient to reach a BER floor. Similarly, for the uplink, it is shown that 35 taps can satisfy the requirement to approach the BER floor. Compared with the downlink, the required number of taps is reduced and the impulse energy is shown to be less spreading. They can be explained by two facts. First, the pre-equalization is operated at 70GS/s (2.8sps for 25Gbaud), whereas the post-equalization is operated at 50GS/s (2sps for 25Gbaud). Second, the BPG used for the uplink has a higher bandwidth than the AWG (~14GHz) for the downlink.

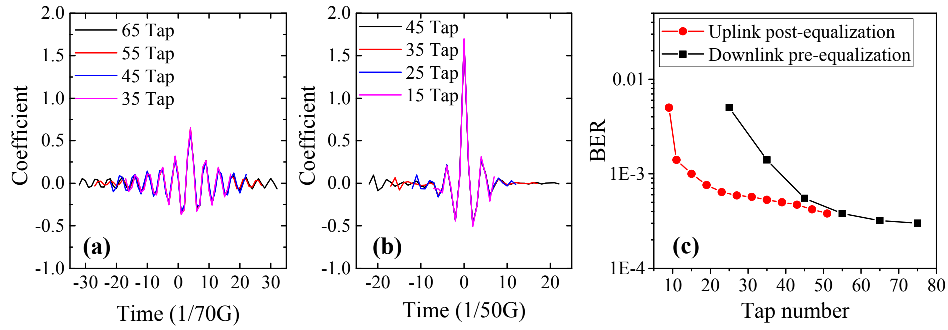

Fig. 5. Time domain filters with various tap numbers for (a) downlink pre-equalization and (b) uplink post-equalization. (c) BER versus tap number for downlink and uplink

3.2.2 Downlink DAC and uplink ADC sampling rate requirement

Next, we investigate the requirement on the DAC/ADC sampling rate. For the downlink DAC, since we have applied an RC filter before the pre-equalization, the signal bandwidth has already been restricted within $\frac{1}{2}R_B(1+\alpha)$. Hence, the minimum requirement of the DAC sampling rate is $R_B(1+\alpha)$ according to the Nyquist sampling theorem. Therefore, to find the required sampling rate, we only need to evaluate the performance with different α values. Figure 6(a) depicts the impact of the RC roll off factor on the BER performance, which shows that the optimal α 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.

For the uplink ADC, since the received signal has already undergone a narrowing effect by the opto-electronics along the transmission link which in fact acts as an anti-aliasing filter, there is no need to adopt an ADC with a sampling rate higher than twice of the baud rate to avoid frequency aliasing. Here, to analyze the required sampling rate, we first down-sample the received signal to a sampling rate between 25 to 50GS/s, which corresponds to an over-sampling ratio of $1 < sps \le 2$. Then, we resample it to 2sps to perform the post-equalization. The BER result after the post-equalization is depicted in Fig. 6(b). It is seen that the BER decreases rapidly when the ADC sampling rate increases from 25GS/s. However, when the sampling rate is higher than ~32GS/s, a BER floor is observed. This implies that the bandwidth of the received signal has already been restricted within ~16GHz by the transmission link, and increasing the sampling rate higher than 32GS/s does not further reduce the frequency aliasing according to the Nyquist sampling theorem. Therefore, we conclude that an ADC with a sampling rate of 32GS/s is sufficient.

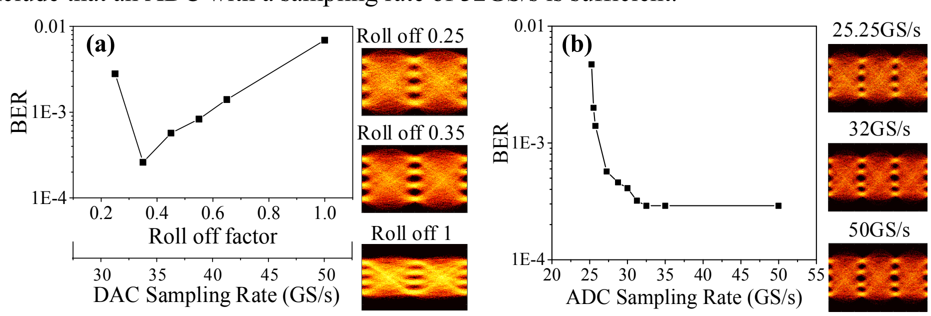

Fig. 6. (a) Impact of the downlink roll off factor on the BER performance and the corresponding required DAC sampling rate, (b) BER performance versus uplink ADC sampling rate.

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3.3 Evaluation on the impact of different ONU receiver responses

In practical deployment, since the transmitter and receiver are at different sites, it is not possible to adaptively learn the downlink pre-equalization filter coefficients for every ONU. A practical approach is to pre-calculate this filter before deployment. However, such a fixed filter may not be able to achieve the optimal performance considering that the responses of different ONU receivers are different due to the imperfect production and the diversity of environmental conditions. Therefore, it is necessary to evaluate the performance sensitivity to variation of ONU responses.

Here, we apply a digital filter to the downlink received signal to emulate the response diversity of the ONU receivers. This digital filter is designed with a roll off of β dB/10GHz from 0GHz to 25GHz as shown in Fig. 7(a), and the detailed implementation procedure is also illustrated. The received signal is first transformed to the frequency domain by DFT followed by a digital filter with different responses, and finally recovered to the time domain by an inverse DFT (IDFT) for BER calculation. The BER performance versus the filter roll off when received power is −12dBm (w/o SOA case) is plotted in Fig. 7(b). It is obvious that optimum BER is achieved when roll off is 0dB/10GHz, and the reason is that the pre-equalization filter at the OLT is obtained when no digital filter is applied at the ONU receiver. The dotted line is the BER when the received power is −13dBm which is at the HD-FEC limit of 3.8×10^{-3} as shown in Fig. 4. This dotted line is used as a reference to evaluate the power penalty: when BER is below this reference, the power penalty will be less than 1dB. Therefore, as per Fig. 7(b), the allowable roll off is from −2.2dB/10GHz to 1.8dB/10GHz when the power penalty is required to be within 1dB. This is in fact a very relaxed requirement. For example, assuming the nominal bandwidth of the end-to-end link is 10GHz@3dB, the allowable bandwidth variation can be from 10GHz@5.2dB to 10GHz@1.2dB.

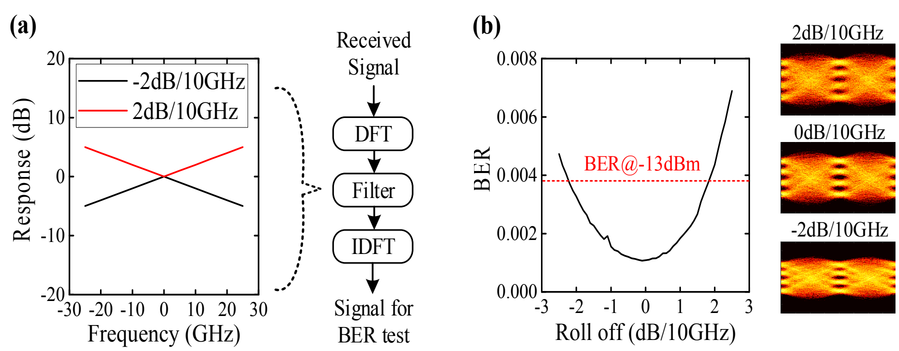

Fig. 7. (a) Procedures for evaluating the response diversity of ONU receivers, (b) BER performance under different filter responses.

4. Results of 25Gb/s OOK and 40Gb/s duobinary PONs

In the above context, we have provided a detailed study on the performance of PAM4 signals with DSP-free ONUs. This section will further evaluate OOK and duobinary signals, which are also popular formats in access networks, to determine their suitable data rates based on the above 10G-class optics. Here, we evaluate 25, 40 and 50Gb/s data rates, as they are target options for beyond 25Gb/s per wavelength PONs.

4.1 25Gb/s OOK PON

The experimental setup of the OOK system is the same as the PAM4 system. Here we first study the data rate that is suitable for OOK format. Figure 8(a) shows the uplink eye diagrams with and without post-equalization in 25 and 40Gb/s cases. For the 25Gb/s case, the received signal manifests as a 3-level duobinary-like signal due to the low-pass filtering effect of the transmission link. When the received optical power is −14dBm, the BER is found to be ~6 × 10^{-3}, which is higher than the HD-FEC limit. In contrast, a decent eye diagram is observed after the post-equalization. For the 40Gb/s case, despite the fact that the received signal also presents a 3-level eye diagram, it is more deteriorated due to the tremendous bandwidth gap between the transmitted signal and the end-to-end link. Consequently, even after the post-equalization, the recovered OOK signal can only achieve a BER around 10^{-2}. Therefore, it is concluded that the suitable data rate for the OOK is 25Gb/s.

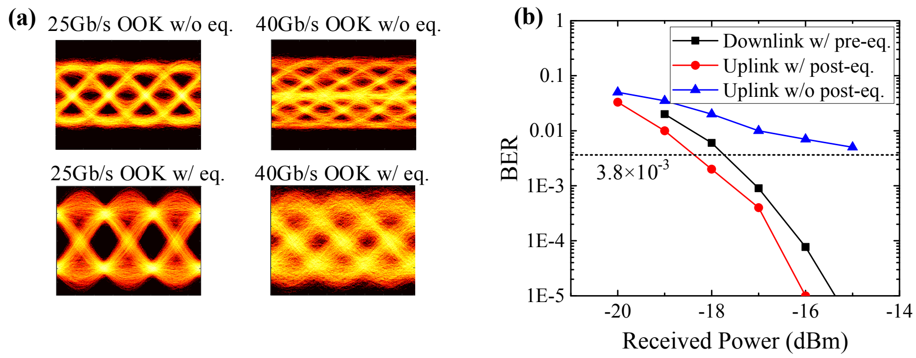

Fig. 8. (a) Uplink OOK eye diagrams w/ and w/o post-equalization when data rate is 25Gb/s and 40Gb/s, (b) downlink and uplink BER performances of 25Gb/s OOK signals.

Figure 8(b) plots the BER performance of the 25Gb/s OOK signals. Only the case without SOA pre-amplification is depicted here. For the downlink, it is shown that the optical sensitivity at the HD-FEC limit is −17.7dBm, while for the uplink the sensitivity is −18.4dBm. The reason behind the sensitivity difference between the downlink and uplink is due to three folds. First, the pre-equalization filter for the downlink is obtained at the DAC sampling rate with 1sps, in which case the timing offset can lead to a non-optimal convergence. Second, although the RF swing has been optimized, the increase in the PAPR caused by the pre-equalization inevitably reduces the available modulation range of the DML. Finally, the bandwidth of the DAC for the downlink is lower than the BPG for the uplink.

4.2 40Gb/s duobinary PON

The experimental setup of the duobinary modulation, as shown in Fig. 9, is different from the PAM4 and OOK. First, the transmitter-side pre-coding is needed for duobinary in order to remove the correlation between adjacent symbols and avoid receiver-side error propagation. As Fig. 9 shows, the encoded OOK sequence b_k is obtained by $(\mathrm{a}_k - \mathrm{b}_{k-1})\,mod\,2$, where a_k is the original OOK sequence and $x\,mod\,y$ represents the modulo-y operation on x. With this pre-coding, each symbol at the receiver side can be demodulated independently simply by module-2 operation. Second, unlike the PAM4 or OOK case where the downlink and uplink use the same format, the duobinary case uses duobinary for the downlink while OOK for the uplink. This is because: 1) for the uplink, OOK is much simpler for ONU, and it can be automatically converted to duobinary by the transmission link and the receiver-side DSP; 2) for the downlink, the 3-level duobinary signal should be generated and pre-equalized at the transmitter, in order to guarantee that an ideal duobinary signal can be obtained at the receiver side. Consequently, for the uplink, the post-equalization at the receiver side is designed to recover the received signals to duobinary as shown in Fig. 9(b), whereas for the downlink, an additional delay and add operation in the transmitter side is used to construct the duobinary signal as shown in Fig. 9(a).

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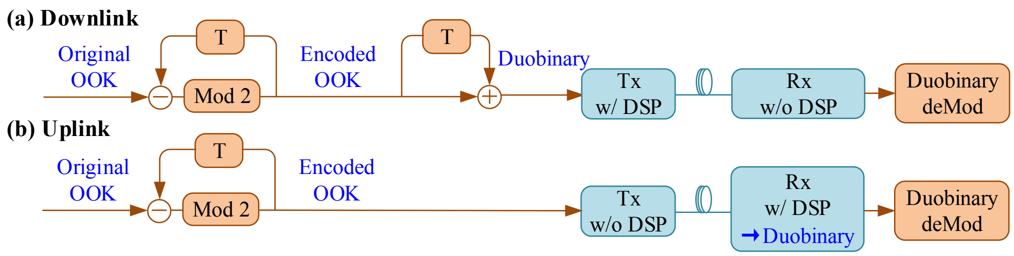

Fig. 9. Setup and pre-coding of the duobinary signal for (a) downlink and (b) uplink.

We then study the data rate that is suitable for duobinary format. Figure 10(a) shows the uplink eye diagrams with and without equalization when received power is –10dBm. A good eye diagram is obtained for the 40Gb/s case after equalization. The eye diagram of the 50Gb/s case is much worse and the BER is around 5×10^{-3}. Therefore, it is concluded that 40Gb/s is more suitable for duobinary. This result is reasonable because the 50Gb/s duobinary signal with a controlled 1-symbol ISI theoretically requires a bandwidth of 25GHz which is far beyond the link bandwidth. Note that pulse shaping is not effective here for duobinary signals because the 50GBaud signal has already been limited within 25GHz by the duobinary shaping. Accordingly, the BER performance (without SOA pre-amplification) of the 40Gb/s signals is plotted in Fig. 10(b). It is shown that the achievable optical sensitivities are –14dBm and –15dBm, respectively for the downlink and uplink. At last, we collect all the achieved sensitivities for PAM4, OOK and duobinary formats without SOA amplification and list them in Table 1. The 50Gb/s PAM4, 25Gb/s OOK and 40Gb/s duobinary respectively achieve a sensitivity of –13.0dBm, –17.7dBm and –14.0dBm.

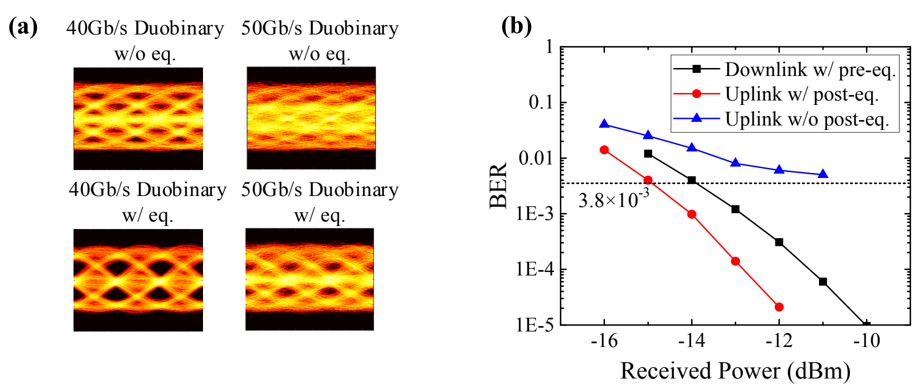

Fig. 10. (a) Uplink duobinary eye diagrams w/ and w/o post-equalization when data rate is 40Gb/s and 50Gb/s, (b) downlink and uplink BER performances of 40Gb/s duobinary signals

Table 1. Optical sensitivities of PAM4, OOK and duobinary formats (w/o SOA case)

50Gb/s PAM4	25Gb/s OOK	40Gb/s Duobinary
–13.0 dBm	–17.7 dBm	–14.0 dBm

5. Summary

In this paper, we have demonstrated and investigated a 50Gb/s per wavelength PON in the O-band without using any DSP in the ONU, meanwhile still adopting low-cost 10G-class optics. In this system, all DSPs are in the OLT side, which includes downlink raised cosine (RC) pulse shaping and pre-equalization, and uplink post-equalization. We show that with an SOA-pre-amplification and commercial 10G-class optics including DML and PD, 50Gb/s PAM4 is realized with a power budget up to 29dB under the HD-FEC BER limit. We present the detailed implementation procedures of the DSP, and conduct a comprehensive study on the system including DSP complexity, DAC/ADC sampling rate and response diversity of ONU receivers. We conclude that, 1) 55 and 35 taps are sufficient for the downlink and uplink, respectively; 2) the minimum requirement of the DAC and ADC sampling rate is 33.75GS/s DAC and 32GS/s, respectively; and 3) with 1dB sensitivity penalty at the HD-FEC, the allowable response diversity of ONU receivers can be from −2.2dB/10GHz to 1.8dB/10GHz. Furthermore, we explore the suitable data rate of OOK and duobinary modulation formats in this system and present their performances. We show that the OOK format is suitable for 25Gb/s data rate with ~5dB sensitivity superiority over the 50Gb/s PAM4 PON, whereas the duobinary format is suitable for 40Gb/s data rate with ~1dB sensitivity superiority.

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