100-Gb/s TWDM-PON based on 10G optical devices

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Abstract: High speed data modulation based on bandwidth limited devices has been considered as a cost-effective way to upgrade 10G-EPON to the next generation 100G-EPON. In this paper, we experimentally demonstrate the modulation, fiber transmission and reception of 25-Gb/s signal based on directly modulated laser and photo-detector both operating at 10 GHz. Instead of digital signal processing, the chirp management, dispersion compensation and frequency equalization in our scheme are realized in optical domain using a single delay interferometer. Three popular formats are investigated, including NRZ-OOK, PAM-4 and duobinary. According to the experimental results, the NRZ-OOK format shows its superiority in both launch power and receiver sensitivity, which provides a cost-effective solution for the construction of 100-Gb/s TWDM-PON.

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

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1. Introduction

Driven by the ever-increasing bandwidth demand of end users, it becomes a necessity that the capacity of optical access networks grows continuously. The recommendation G.989, which is currently under final definition by ITU-T, suggests that next generation passive optical network stage 2 (NG-PON2) will be established based on time and wavelength division multiplexing (TWDM) architecture. Four 10G-PONs are stacked to provide 40-Gb/s aggregate capacity [1]. However, it would not provide a long-term satisfaction for the desire of users, so research for the next generation Ethernet PON (EPON) comes out on its heel, aiming at providing a capacity of 100-Gb/s [2]. The common solution for 100-Gb/s capacity is stacking four wavelengths with 25 Gb/s bit rate on each. Generally, it's preferred to use 10-G class optical devices for cost control, therefore advanced modulation formats with higher spectral efficiency are required. Experimental demonstrations of 25 Gb/s or even 40 Gb/s modulation on a single wavelength have been reported based on four-level pulse amplitude modulation (PAM-4) [3] and duobinary [4] formats. Electro-absorption modulated laser (EML) [5] or Mach-Zender modulator (MZM) [6] are used as transmitters, and the chromatic dispersion induced signal distortion is compensated by digital signal processing (DSP) or fiber Bragg grating (FBG). Formats comparison between duobinary and PAM-4 format has been reported by J. L. Wei et al. using EML based transmitters [7]. However, in recent years, there is growing concern about the usage of directly modulated laser (DML) in PON systems due to its price advantage [8]. Several experiments reporting the use of commercially available DMLs operating at 2.5 Gb/s and 10 Gb/s in TWDM-PONs have been performed recently. Electrical dispersion compensation (EDC) [9], optical spectral reshaping [10] and advanced modulation techniques [11] have been presented to deal with the transmission distance limitation caused by the interaction between laser chirp and fiber dispersion, by which 40-km and 100-km [12] single mode fiber (SMF) transmission of 10-Gb/s directly modulated signal have been realized with ignorable sensitivity penalty. But the feasibility of using DML in 100 Gb/s TWDM-PON systems has not been investigated thoroughly yet.

We previously demonstrated the modulation and detection of 28-Gb/s duobinary signal using DML and PIN both operating at 10 GHz, where a single delay-interferometer (DI) reshapes the optical spectrum to realize the chirp management and enable 40-km single mode fiber (SMF) transmission [13. In this paper, we found that taking advantage of the high-pass filtering effect of the DI based optical spectral reshaping, the duobinary signal can be recovered back into non-return-to-zero on-off-keying (NRZ-OOK) format as long as the data rate is reduced to 25 Gb/s. In this case, the DI works as a dispersion compensator and also an optical frequency equalizer (OEQ) at the same time. We call the generated NRZ-OOK format in this scheme as NRZ-OEQ. Moreover, we apply the optical chirp management technique to PAM-4 format. As a result, the modulation and 40-km fiber transmission of NRZ-OEQ and PAM-4 formats both operating at 25 Gb/s are realized using the same devices as in [13]. The

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key parameters in the high bit-rate PON are experimentally evaluated, including the optical power budget, the dispersion tolerance and the cost. It turns out that NRZ-OEQ shows superiority over PAM-4 and duobinary in most aspects, which could be a promising candidate for 100G PON construction. This paper is organized as follows. First, we describe the network architecture and the experimental setup, then we outline the generation and detection of NRZ-OEQ and PAM-4 signal respectively. Finally, we summarize the experimental results and make a discussion.

2. Proposed 100-Gb/s TWDM-PON scheme

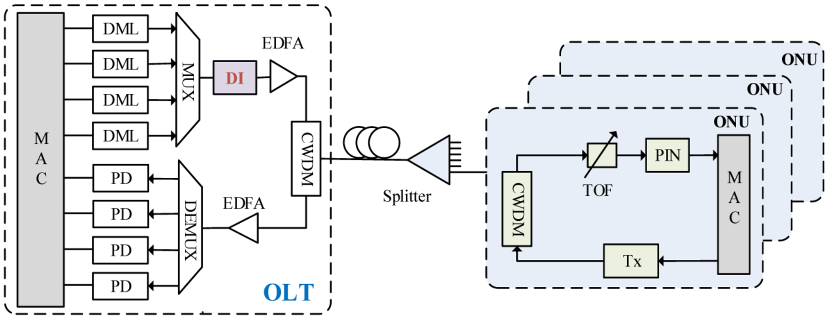

Fig. 1. Proposed 100-Gb/s TWDM-PON system.

Figure 1 shows the network configuration of the DML based 4 × 25-Gbs TWDM-PON. In the optical line terminal (OLT) side, four DMLs operating at wavelengths spacing of 100/200 GHz are used as transmitters. The data is directly modulated on the lasers. After wavelength multiplexing, the four downstream channels are launched into a DI for spectral reshaping. Note that due to the periodical characteristic, a single DI can work for all the four channels as long as the free-spectral-range (FSR) is properly set. Then an erbium-doped fiber amplifier (EDFA) boosts the signal power for loss budget improvement. After fiber transmission, the signal is distributed to all ONUs by a power splitter. The receiver in the optical network unit (ONU) consists of a tunable optical filter (TOF) for wavelength selection and a PIN-TIA for signal detection. Coarse wavelength division multiplexers (CWDMs) are used in the system for combining/separating the upstream and downstream wavelengths. Note that the optical devices for transmitting Duobinary, PAM-4 and NRZ-OEQ signals are all the same, and the only difference lies in the signal generation part, which will be illustrated in detail in the following section.

3. Experimental setup

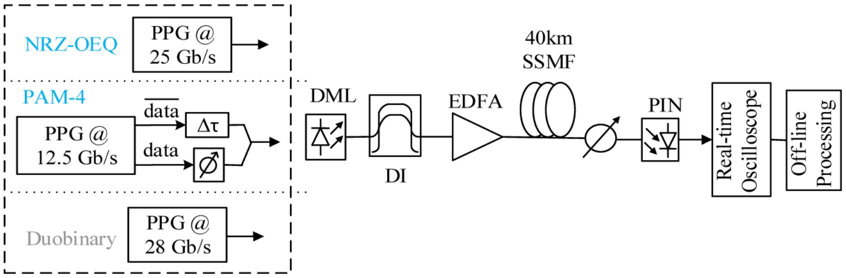

Fig. 2. Experimental setup.

In order to investigate the performances of PAM-4 and NRZ-OEQ modulations, we set up an experiment as shown schematically in Fig. 2. Only one channel is demonstrated for the proof of concept. The optical devices in both transmitter and receiver sides are the same as in [13].

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The transmitter is a commercially available directly modulated 10-GHz DFB laser (XGT-9005A). The output wavelength of the DML is ~1543 nm under room temperature and it has a thermally controlled wavelength tuning range of ~3 nm. The laser is biased at ~80 mA to get the optimal modulation performance. The DI (Kylia-WT-MINT) has an FSR tunable from 10 GHz to infinite, which can serve as a periodical, bandwidth tunable optical notch filter for multi-channel operation. After 40-km fiber transmission, a variable optical attenuator (VOA) emulates the function of splitter to attenuate the signal power, and launches the signal into the 10-GHz PIN (Conquer-KG-PR-10G) for detection. The 25-Gb/s binary data sequence is generated by pulse pattern generator (PPG, Keysight N4960A). As there is no real-time PAM-4 evaluation board in our lab, the PAM-4 signal is generated by manipulating the magnitude and delay of two PRBS signals, and then combined the two signals as an electrical PAM-4 signal. At the receiving side, the signal is captured by a digital storage oscilloscope (DSO) with 80-GS/s real-time sample rate. Signal demodulation and bit error ratio (BER) calculation are realized by off-line DSP in Matlab. Note that the off-line DSP is required just for level determining and BER calculating, and no signal recovery module such as frequency equalization or dispersion compensation is applied. Besides, in order to make a fair comparison, the BER measurement of OOK signal is also performed off-line in Matlab.

4. Experimental demonstration of NRZ-OEQ

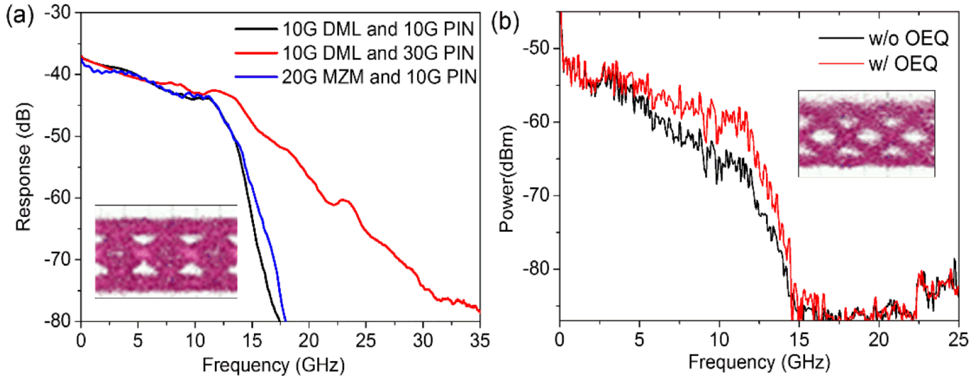

Fig. 3. (a) Frequency response of DML and PIN, (b) signal spectrum of 25-Gb/s OOK signal with and without OEQ.

Figure 3(a) shows the measured frequency responses of the transmitter and receiver with different devices combination. The use of 30G PIN and 20G MZM in the measurement is for separately evaluating the bandwidth of the 10G DML and 10G PIN. The combination of the 10G DML and 10G PIN has a 3-dB bandwidth of 6 GHz and a 10-dB bandwidth of ~12 GHz, which is sufficient to support 25 Gb/s PAM-4 modulation. But for binary modulation, the eye diagrams will be gradually closed as the data rate further increases. With a data rate higher than 25 Gb/s, the OOK signal will be converted into duobinary format as the inset shows. The signal can either be demodulated as duobinary format by three-level decision, or be recovered back to binary format using frequency equalization techniques. Optical spectral reshaping based frequency equalization has been presented to increase the frequency response of bandwidth-limited transmitters, realizing 10-Gb/s operation of 2-GHz reflective semiconductor amplifier (RSOA) [14] and 40-Gb/s operation of 10-GHz DML [15]. However, the bandwidth requirement on the receiver was not reduced and the transmission distance is limited [16]. Here we will present the feasibility of using a single DI for simultaneous frequency equalization and chirp management of 25-Gb/s directly modulated signal, where the bandwidth requirement on both transmitter and receiver are reduced to 10 GHz and the transmission distance is increased to 40 km.

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Figure 3(b) shows the electrical spectrum of the received 25-Gb/s signal. Due to the limited bandwidth of both transmitter and receiver, the high frequency components are highly attenuated. However, as we add a DI between the DML and the PIN to partially suppress the lower-frequency components in the optical spectrum, the power on the high frequency region can be enhanced as depicted in Fig. 3(b). In this way, the optical frequency equalization is realized and the eye diagrams become open as the inset shows. Note that the effect of the DI-based frequency equalization is limited, so if we further increase the data rate, the eye diagram will gradually close again, and the signal must be demodulated as duobinary format as in [13]. On the other hand, for effective chirp management, the DI should also suppress the long-wavelength components of the optical signal to realize frequency to intensity conversion. Therefore, for simultaneous optical frequency equalization and chirp management, the notch of the filter should be positioned at the longer waveband of the optical spectrum nearby the carrier, as Fig. 4 shows. The optical spectrum of the original directly modulated signal and the filtered one are also depicted.

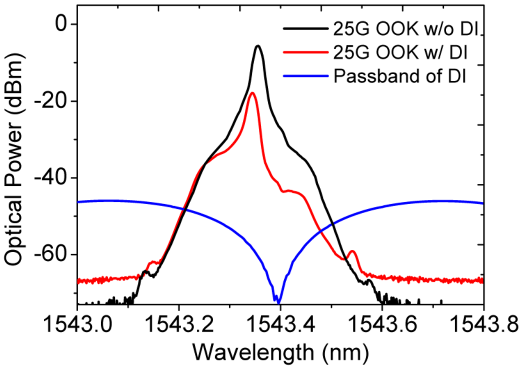

Fig. 4. Optical spectrum of the 25-Gb/s OOK signal before and after DI.

Figure 5 shows the measured eye diagrams of the original and filtered directly modulated signal in BtB, 20-km and 40-km fiber transmission cases, from which we can clearly observe the signal quality improvement benefited from the frequency equalization and chirp management effects of the DI. Note that both the frequency equalization and chirp management performances are closely related with the wavelength offset between the signal and the DI notch band, while the requirement on the DI bandwidth is quite loose. When we vary the FSR of the DI from 0.4 nm to 2 nm, similar results are obtained. Therefore the FSR can be freely selected according to the channel spacing to enable multi-channel operation. But the signal quality is quite sensitive to the wavelength drifts from either the DML or the DI. Experimental results show that ~1-dB penalty will be introduced when the wavelength offset varies within ± 1 GHz around the optimal value of 12.5 GHz. And the penalty will be increased to ~3 dB when the wavelength offset drifts up to ± 3 GHz. Therefore, to keep the system operating stably, the operating wavelengths of both the DML and the DI should be precisely locked just like in the chirp managed laser (CML) construction or temperature-insensitive DI should be used.

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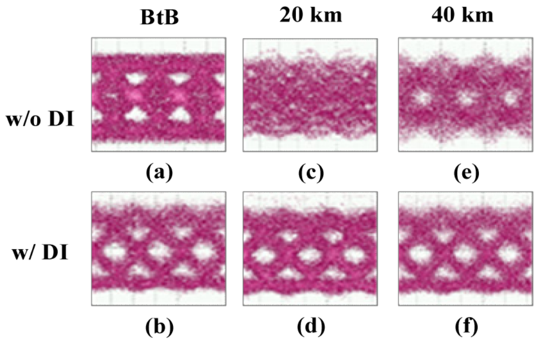

Fig. 5. Eye diagrams of the 25-Gb/s OOK signal with and without DI in BtB, 20-km and 40-km fiber transmission cases.

Finally, we measured the BERs of the 25-Gb/s signal in BtB, 20-km and 40-km fiber transmission cases. The results are shown in Fig. 6. Without the spectral reshaping of DI, we cannot obtain BER lower than 3.8×10^{-3} even in BtB case. After the equalization of DI, the eye diagrams open clearly with a sensitivity of ~-19 dBm at BER of 1×10^{-3}. 20-km fiber transmission results in ~1.2-dB sensitivity penalty. And an extra 0.2-dB penalty is introduced when the fiber length extends to 40 km, verifying the feasibility of using a single device for simultaneous frequency equalization and chirp management. Moreover, due to the chirp induced spectral broadening, the peak carrier intensity of the directly modulated signal is much lower as compared to the external modulated signal, thereby showing a higher tolerance to fiber nonlinearity [17]. In the experiment, no sensitivity degradation is observed until the launch power exceeds 18.5 dBm. As a result, the total loss budget for a single channel is 36 dB, which could support 40-km fiber transmission and 128 users with sufficient margin.

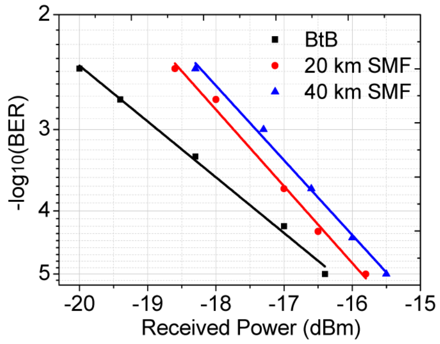

Fig. 6. Measured BER curves of the 25-Gbs NRZ-OEQ signal in BtB, 20-km and 40-km fiber transmission cases.

5. Experimental demonstration of PAM-4

The experimental demonstration for PAM-4 is quite similar with the duobinary and NRZ-OEQ cases. The 25-Gb/s PAM-4 signal with 1.8V peak-to-peak power is directly modulated to the DML. DI-based optical spectral reshaping is also required for chirp management, otherwise the signal would be severely distorted by chromatic dispersion after 20 km and 40 km fiber transmission as Fig. 7(ii) shows. Fig. 7(v) plotted the optical spectrum of 25 Gbps PAM4 signal before and after the DI. The wavelength offset between the signal and notch of the filter should be kept at ~0.1 nm, and the FSR of the DI can be flexibly tuned from 0.25 nm to 2 nm. Benefited from the spectral reshaping induced equalization effect and ER improvement, the signal sensitivity measured in BtB case is increased by 4 dB after filtering. The BERs in BtB, 20 km and 40 km transmission cases are calculated using Matlab, and the results are depicted in Fig. 8. The signal has a sensitivity of ~-11dBm in 20-km and 40-km transmission cases and ~-12.5 dBm in BtB case. Also, the nonlinear tolerance is higher than external modulation cases due to the chirp induced spectral broadening, and the maximal launch power is measured to be 15 dBm. Therefore, the total loss budget is 26 dB, which is 10-dB lower than the NRZ-OEQ solution.

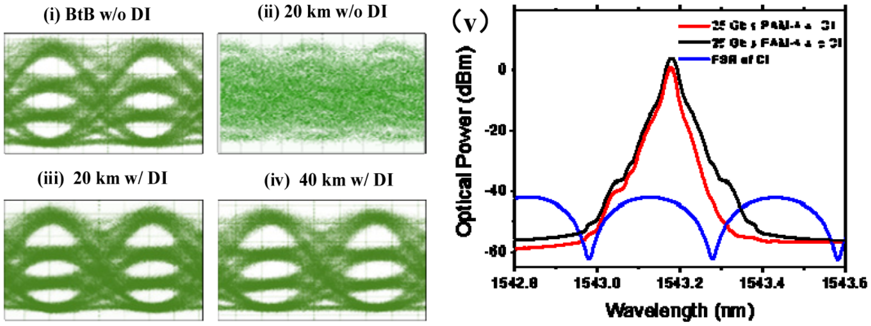

Fig. 7. (i)-(iv) Measured eye diagrams and (v) optical spectrum of 25-Gb/s PAM-4 signal.

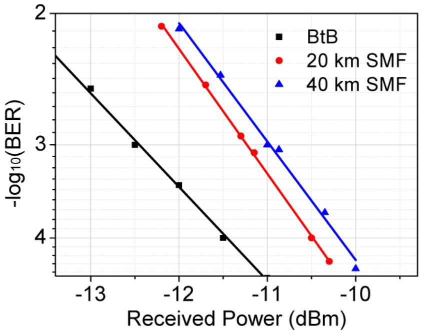

Fig. 8. Measured BER of 25 Gb/s PAM-4 signal.

6. Discussions and conclusions

We have demonstrated the 25 G/s operation of 10G optical devices using three most popular formats: NRZ-OEQ, PAM-4 and duobinary [13]. For applications in future PON systems, there are some key issues need to be concerned, including the dispersion tolerance, the cost and the loss budget requirement as well. Table 1 summarizes the key parameters in each solution for comparison. Firstly, thanks to the effectiveness of the DI-based optical chirp management, fiber dispersion is no longer an issue for all three formats within 40-km SMF transmission. Secondly, the requirement on the optical devices are all the same. Therefore, the cost difference mainly comes from the electrical devices in the signal generation and decision parts. The demodulation technique for 25-Gb/s NRZ-OEQ signal is quite mature and the clock-data recovery (CDR) chips are already commercially available. The real-time decision circuit for duobinary format has been reported with a data rate up to 40 Gb/s [18]. As for PAM-4 format, decision chip operating at 22 Gb/s has been presented based on 90-nm CMOS-SOI technology [19], and 40-Gb/s real-time operation is realized by evaluation board [20]. By comparison, the demodulation of NRZ-OEQ format is most mature and costs the least. In terms of the performance, the lower extinction ratio of the multi-level signal increases the decision difficulty and decreases the tolerance to the noise and fiber nonlinearity. As a result, the NRZ-OEQ signal shows superiority in both launch power and receiver sensitivity. Note that as the duobinary signal is generated by the low-pass filtering effect of the bandwidth-limited transceivers, the best signal quality is obtained at 28 Gb/s

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rather than 25 Gb/s. For 100G-PON application where 25-Gb/s per wavelength is required, NRZ-OEQ outperforms the other two formats. However, with a higher spectral efficiency, duobinary and PAM-4 signals have the potential to support higher data rate, showing their superiority over binary format in the aspect of capacity. The detailed parameters are listed in Table 1 for comparison. The NRZ-OEQ modulation provides 36-dB loss budget, which is 5-dB higher than the duobinary format and 10-dB higher than the PAM-4 case. For multi-channel operation, at least 3-dB insertion loss from the wavelength selection filter in ONU should be considered. Also, the launch power should be lower than single channel case to avoid fiber nonlinearities. But the loss budget degradation can be fully compensated by replacing the PIN with an APD or an integrated SOA-PIN detector [21] for sensitivity improvement.

Table 1. Comparison of NRZ-OEQ, Duobinary and PAM-4 formats

	Bit rate (Gb/s)	Reach (km)	Launch power (dBm)	Sensitivity (dBm)	Loss budget (dB)	Cost
NRZ-OEQ	25	40	18.5	−17.5	36	Low
Duobinary	28	40	16	−15	31	High
PAM-4	25	40	15	−11	26	High

In this paper, we experimentally investigated the 25-Gb/s operation of 10-GHz DML and 10-GHz PIN for 100G-PON systems. Three popular formats are demonstrated, including NRZ-OEQ, PAM-4 and duobinary. A DI reshapes the optical spectrum of all the three formats to enable 40-km fiber transmission, and it also optically equalizes the signal spectrum to realize duobinary-to-binary conversion in 25-Gb/s data rate. By comparison, the proposed NRZ-OEQ format has advantage in both cost and performance aspects, which is a viable candidate for future 100G-PON systems.

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