Symmetric 100-Gb/s TWDM-PON in O-Band Based on 10G-Class Optical Devices Enabled by Dispersion-Supported Equalization

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***Abstract*—Increasing the serial bitrate to 25-Gb/s per channel as well as coexisting with the same optical distribution network of the 10G-ethernet passive optical network (EPON) is challenging. The bandwidth limitation and the reduced dispersion tolerance at high date rate make it much more difficult to achieve higher loss budget. In this paper, we have first shown a demonstration of a symmetric 4 × 25-Gb/s time-wavelength-division-multiplexed passive optical network system based on nonreturn-to-zero on-off-keying format supporting 0–20 km reach in O-band. 10G-class directly modulated lasers (DMLs) are employed to serve as both upstream and downstream transmitters owing to the low cost and the frequency chirp induced by DML can be used for bandwidth equalization. Instead of using digital signal processing, the chirp management and frequency equalization are simultaneously realized in optical domain through our proposed dispersion supported equalization technique. By employing a spool of dispersion-shifted fiber in optical line terminal (OLT), a single device can be used to simultaneously equalize the frequency response of multiple downstream and upstream channels. Then, we further use a semiconductor optical amplifier as a booster and preamplifier at the OLT for downstream and upstream, respectively. A power budget of 26 and 32 dB with 0–20 km reach of standard single mode fiber for downstream and upstream transmission at 1310 nm is obtained. The experimental results shown in this paper reveal that our proposed cost-effective scheme would be a promising candidate for the next generation 100G-EPON.**

***Index Terms*—Frequency equalization, loss budget, modulation format, NRZ-OOK, time-wavelength-division-multiplexed passive optical networks.**

I. INTRODUCTION

DRIVEN by the broadband applications such as cloud services, HD and virtual video, the bandwidth demand in optical access network have grown tremendously in recent years [1]. Recently the studies for next generation PON focus on the symmetric capacity of 100-Gb/s with 25-Gb/s per wavelength in both upstream and downstream link and the 100G-EPON standardization is currently in progress with the IEEE 802.3ca task force [2]. Since low-cost is one of the most notable features in access network, the off-the-shelf low cost 10G class optics are reused to keep cost to a minimum. Previously, several experiment demonstrations of 25-Gb/s data rate transmission based on 10G-class optical devices have been reported for discussion. Advanced modulation formats, such as four-level pulse amplitude modulation (PAM-4) [3]–[5], electrical duobinary (EDB) [6]–[8], optical duobinary formats (ODB) [9]–[11], combined with digital signal processing are the universal solutions. Since commercial clock-data recovery (CDR) chips for real-time two-level detection is easy to be realized, NRZ-OOK format is more cost-efficient for commercial deployment. In [12], 25-Gb/s NRZ signal have been demonstrated based on 10G optics, digital predistortion and DSP aided detection have been used to equalize the bandwidth. Therefore, it is challenging to transmit 25-Gb/s NRZ-OOK signal based on 10G-class optical devices without DSP for equalization. In our previous work [13], an optical delay interferometer (DI) instead of DSP is used for frequency equalization. Disadvantage of using DI to equalize the bandwidth is that it is unsuitable in the upstream due to burst wavelength drift. In [7], [14], upstream 25-Gb/s serial rate is demonstrated based on EDB and PAM-4. However, low cost real-time burst mode (BM) receivers for EDB and PAM-4 are not commercialized yet. Therefore, the upstream capacity upgradation to 25-Gb/s based on NRZ format is required to further investigate. To our knowledge, there has been no symmetric real-time 100G-PON demonstrations yet since the low-cost 25-Gb/s upstream solution is more challenging. Besides, all the above-mentioned demonstrations are based on C-band wavelength plan. The wavelength plan for 100G-EPON is still under investigation in IEEE 802.3ca. At present, there are four major wavelength plans being considered in the 802.3ca project [15]. O-band wavelength plan is preferred especially in upstream since it has low dispersion properties and we can leverage high volume data center O-band DMLs and external modulated lasers (EMLs). Moreover, to improve the loss budget in O-band, SOA is an appropriate choice as an optical amplifier due to the small form factor and fast carrier dynamics.

In our previous report [16], we have firstly shown a demonstration of symmetric 100G-PON based on NRZ-OOK format in O-band without DSP for equalization. A spool of DSF with

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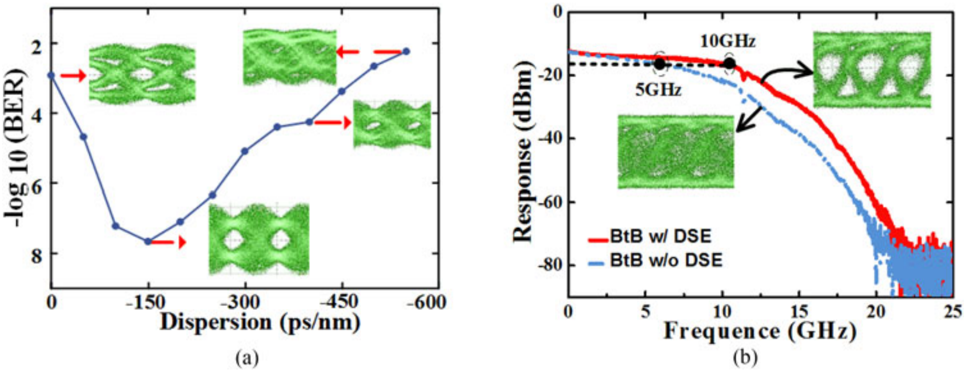


(a) (b)

Fig. 1. (a) BER evolution with dispersion value of 25.78-Gb/s NRZ-OOK signals; (b) Frequency response of transceivers and corresponding eye diagrams of 25.78-Gb/s NRZ-OOK signals before and after DSE at 1310 nm.

around -150 ps/nm dispersion at 1310 nm is used in OLT to compress the pulse width of directly-modulated signals and equalize the frequency response for all downstream and upstream channels. The 3-dB bandwidth of the system is improved from 5 GHz to 10 GHz. Besides the negative dispersion generated by DSF at 1260 nm and 1360 nm is -200 ps/nm and -100 ps/nm respectively which are within the tolerance range of DSE technique, therefore the DSE technique based on DSF is almost wavelength-insensitive thus supporting un-cooled lasers with large wavelength drift, which is the real case for most lasers commonly used in O-band. The cost of DSF is shared by all users therefore it can be neglected, ensuring it outperforms other DSP-based equalization techniques. At the same time, a bit-error rate tester (BERT) with embedded CDR chip is used for real-time BER measurement therefore no pre-FEC DSP is required. For 25.78-Gb/s data rate, we can achieve -17 dBm receiver sensitivity (defined at BER of 1×10^{-3}) after 20-km reach for all downstream and upstream channels. However, the DSF with 10 dB insertion loss needs to be compensated to improve the loss budget.

In the current paper, we further deepen and expand on our results in [16]. To investigate the principle of DSE, we analyze the changes in optical spectrum. Moreover, we adjust the operating current and modulation voltage of the DML to optimize the performance of DSE function. Then, we employ a SOA to compensate the loss of the SSMF and all the passive components including the DSF. Detailed analysis of the power budget for the downstream link is investigated to get the optimal output power of SOA before being launched into the fiber. For the upstream, we also evaluate the evolution of the receiver sensitivity after employing a SOA as pre-amplifier. Considering all the optical/electrical devices are commercially available and with low cost, we believe this will be an attractive solution for the upcoming deployment of symmetric 25-Gb/s TDM-PON or symmetric 100-Gb/s TWDM-PON.

The structure of this paper is as follows: in Section II, we explain the principle of our proposed DSE technique. Section III presents the experimental setup and the optimization of the system performance. In Section IV, we evaluate the whole symmetric 100G TWDM-PON system performance and use a SOA for power budget improvement. Section V concludes the paper.

II. PRINCIPLE

The optical signal generated by DML is more sensitive to fiber dispersion for the chirp-induced optical spectrum broadening [17]. However, when the signal with positive frequency chirp transmit in negative dispersion fiber, the signal quality will be better than chirp-free signal [18] and 10-Gb/s date rate long reach transmission can be achieved [19]. For a bandwidth-limited direct modulation and direct detection (DM-DD) system, the rise/fall time of the output pulse is large, resulting in a closed eye for high bit rate modulation. But after transmission in negative dispersion fiber with proper distance, the rise/fall time of the pulse can be minimized attributed to the positive chirp characteristics of the DMLs [20], corresponding to the high-frequency components enhancement and open eyes. We name this technique as DSE.

The amount of negative dispersion needs to be optimized to achieve the best eye opening. Since a tunable dispersion compensator (TDC) in O-band is not available in our lab, we first evaluate the BER evolution of a 25.78-Gb/s NRZ-OOK signal with negative dispersion in C-band at back to back (BtB) case using a TDC (II-VI network solutions PS3200 consisted of 16 cascaded G-T etalon cavities) with maximal tuning range from -2100 ps/nm to $+2100$ ps/nm. 10G-class C-band DML and PIN are used as transmitter and detector respectively. As shown in Fig. 1(a), the BER performance is improved first and then degraded when the dispersion value exceeds -150 ps/nm. The reason is that the redundant negative dispersion will degrade signal after compensating the DML chirp. The optimal dispersion compensation value is between -100 ps/nm and -200 ps/nm. In order to generate the needed negative dispersion, we use a spool of 10-km DSF with around -150 ps/nm dispersion at 1310 nm in the experiment. Note that any other dispersive components with negative dispersion in O-band can be used. Then, the bandwidth evolution of the end-to-end system composed of 10 Gbps O-band DML and APD is measured by an electrical vector network analyzer and the corresponding eye diagrams of 25.78-Gb/s NRZ signal in the system are also measured. The results are shown in Fig. 1(b). It can be observed that the eye diagram is completely closed since the 3-dB bandwidth of the system without DSE is only 5 GHz. After employing DSF for

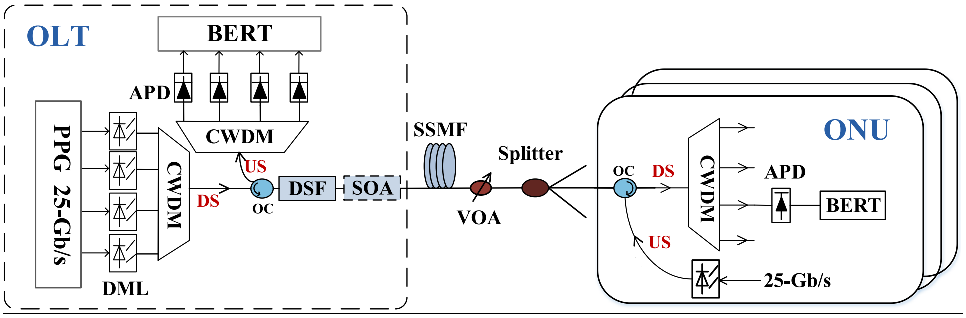


Fig. 2. Experimental setup for symmetric 100G-PON.

equalization, the 3-dB bandwidth is improved to 10 GHz and the eye diagram turns to be open, which can further prove the frequency equalization effect of the DSE technique. It is noted that the dispersion value of DSF may not be optimal for O-band laser, therefore further analyses of the BER performance under different chirp with fixed dispersion have also been demonstrated in part III B. The bandwidth equalization of DSE technique is achieved in optical domain rather than in electrical domain, which significantly simplifies the complexity of high date rate signal processing. Besides, compared with C-band case, DSE technique is more flexible to be used in O-band. As we know, the SMF will introduce a certain amount of positive dispersion to optical signal in C-band, the negative dispersion of the compensator will be required to first compensate the fiber dispersion and then equalize the bandwidth. Therefore, the negative dispersion compensation value will be different for users located at different distance from OLT, which is not flexible for deployment. However, the problem can be neglected in O-band due to the zero-dispersion character of the fiber in this range.

III. ARCHITECTURE DESIGN FOR 100-GB/S TWDM-PON

A. *Experimental Demonstration*

Fig. 2 shows the experimental setup of the symmetric 100-Gb/s TWDM-PON. The aggregate data rate of symmetric 100-Gb/s is achieved by stacking four pairs of wavelengths in both upstream and downstream directions. In the OLT side, the 25.78-Gb/s NRZ-OOK signal is generated by a pulse pattern generator (PPG, Keysight N4960A) with $2^{31} - 1$ pseudo random binary sequence (PRBS) pattern. The generated electrical signals with a peak-to-peak voltage of 1.5 V are loaded onto the DMLs to achieve E/O conversion. The output signals from four DMLs operating at 1270 nm, 1290 nm, 1310 nm and 1330 nm respectively are multiplexed by an O-band coarse wavelength-division-multiplexer (CWDM) with 20 nm channel spacing and ± 7.5 nm channel passband. An optical circulator (OC) is used to separate the downstream and upstream signals, where the upstream channels are operated at the same waveband with the downstream ones and with around 200 GHz wavelength deviation. Fig. 3 shows the measured optical spectra for downstream and upstream after the CWDM mux. Since the wavelength plan has not been finalized in IEEE NG-EPON, the used wavelengths in the experiment are based on the availability of the DMLs of O-band. The upstream signals are de-multiplexed by another O-band CWDM and sent into APDs for detection. The BER is real-time measured by a BERT with embedded CDR (Steligent BT6201). Following the OC, a spool of 10-km long DSF with the total dispersion of -150 ps/nm and 10-dB insertion loss at 1310 nm is used for DSE function for both downstream and upstream channels. We employ a SOA (Thorlabs' BOA1017S) to compensate the insertion loss and improve the system loss budget, which is demonstrated in part IV C. The SOA has a saturation output power of 17 dBm and 7 dB noise figure at 1310 nm. After 20-km SSMF transmission, a variable optical attenuator (VOA) is employed to emulate a passive splitter and is also used to vary the input power for receiver sensitivity measurement. In the ONU side, another OC is used to separate the downstream and upstream signals. To select one of the four downstream wavelengths, a same CWDM as in OLT is employed to act as a wavelength selective filter. Then the received signal of one downstream channel is detected by a 10 Gbps APD. We also employ the BERT for real-time BER measurement in ONU. As for the upstream transmission, a 10 Gbps DML is employed to carry the 25.78-Gb/s users' data. All the DMLs/APDs are commercialized 10 Gbps components and the same type is used in both OLT and ONUs, which are the key components to ensure the low cost.

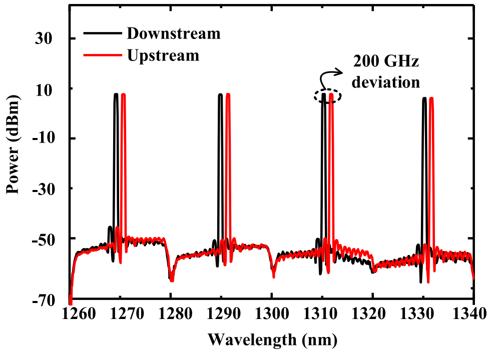


Fig. 3. Optical spectra for downstream and upstream.

B. *System Performance Optimization*

The chirp induced frequency shift which includes both transient and adiabatic chirps will broaden the spectrum. Fig. 4

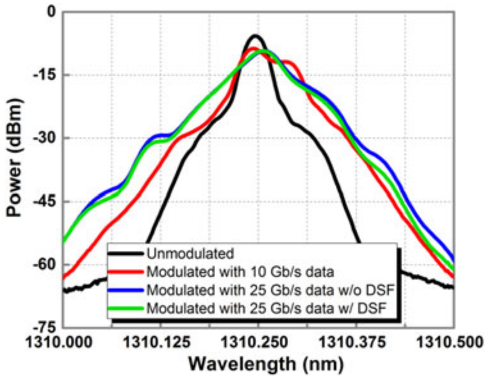


Fig. 4. The optical spectra of one downstream wavelength with and without DSF.

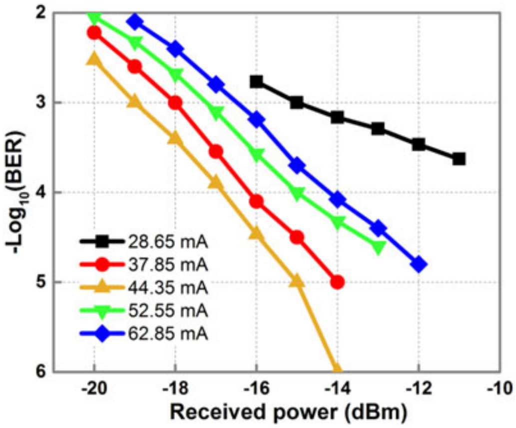


Fig. 5. BER performance versus received power for different operating current.

shows the optical spectrum evolution after being modulated with different data rate signal with and without DSF which are measured by an optical spectrum analyzer (OSA, YOKOGAWA AQ6370C) with 0.02 nm wavelength resolution. It can be observed that the optical spectrum is broaden and shows asymmetry after the modulation of 10-Gb/s NRZ-OOK signal. And the central frequency for the '1s' and '0s' is different due to the adiabatic chirp. However, the transient chirp will become dominant under higher data rate modulation which makes the adiabatic chirp undistinguishable. Thus, after being modulated with 25-Gb/s NRZ-OOK signal, the central wavelength shift is unobvious as the 10-Gb/s case. After employing DSF to the 25-Gb/s signal, we can observe that the spectrum is narrowed at the sidelobe rather than broaden. Therefore, the spectrum broadening induced by chirp can be restrained by DSE technique.

The performance of DSE technique is related to the DML chirp which can be varied by adjusting the operating current and modulation voltage. We evaluate the BER performance of 1310 nm channel for 25.78-Gb/s NRZ-OOK signal transmission based on 10G DML and APD at BtB case with DSF. We first biased the DML at different operating current and fixed modulation voltage. To avoid nonlinearities induced by the DSF at different input power, we use a VOA to keep the injection power at 5 dBm. The BER results are shown in Fig. 5. It can be observed that the optimal operating current of DML is around 44.35 mA with 8 dBm output power. The sensitivity will significantly degrade with higher operating current. As mentioned above, the transient chirp becomes dominant in high data rate transmission and it will decrease with the increase of the operating current [21]. As for the modulation voltage, we choose four different cases for comparison: 0.8 V, 1.2 V, 1.5 V and 1.8 V, the results are shown in Fig. 6. The DML is biased at fixed operating current with 8 dBm output power. Although the higher modulation voltage can improve the extinction ratio of the signal, it will also cause the adiabatic chirp increasing at the same time [21]. It can be observed that the performance is improved with the increase of modulation voltage, but the improvement of sensitivity becomes smaller and smaller. Note that we choose 1.5 V for the whole experiment test since the sensitivity improvement is within 0.5 dB when the modulation voltage varies from 1.5 V to 1.8 V. To further ensure whether the modulation voltage induced chirp will affect the performance of DSE technique, we also measure the frequency response of the system with different voltages of the radio signal from network analyzer under fixed operating current. The 3-dB bandwidth shows no difference between each case, which indicates that the adiabatic chirp induced by modulation voltage is not the favorable factor for the equalization effect.

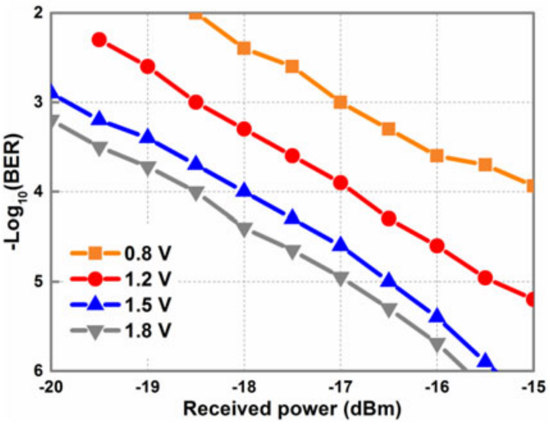


Fig. 6. BER performance versus received power for different modulation voltage.

IV. EXPERIMENTAL RESULTS

A. *Eye Diagrams for All Downstream Channels*

For downstream, we propose to use 10G-class DML and APD to realize 25.78-Gb/s transmission based on NRZ format. The eye diagrams of downstream 25.78-Gb/s NRZ-OOK signals at BtB and 20-km reach with and without DSF for different wavelengths are shown in Fig. 7. As the system 3-dB bandwidth is only 5 GHz, we can see the eye diagram of 25.78 Gbps NRZ signal is completely closed. Thus, a spool of 10-km DSF with about -150 ps/nm negative dispersion is deployed to achieve the frequency equalization and enhance the high-frequency response of the bandwidth-limited system. As mentioned in part II, the 3-dB bandwidth is improved to 10-GHz. Therefore, we

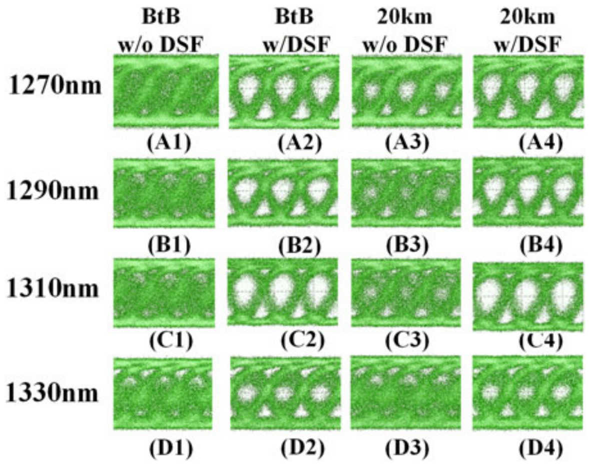
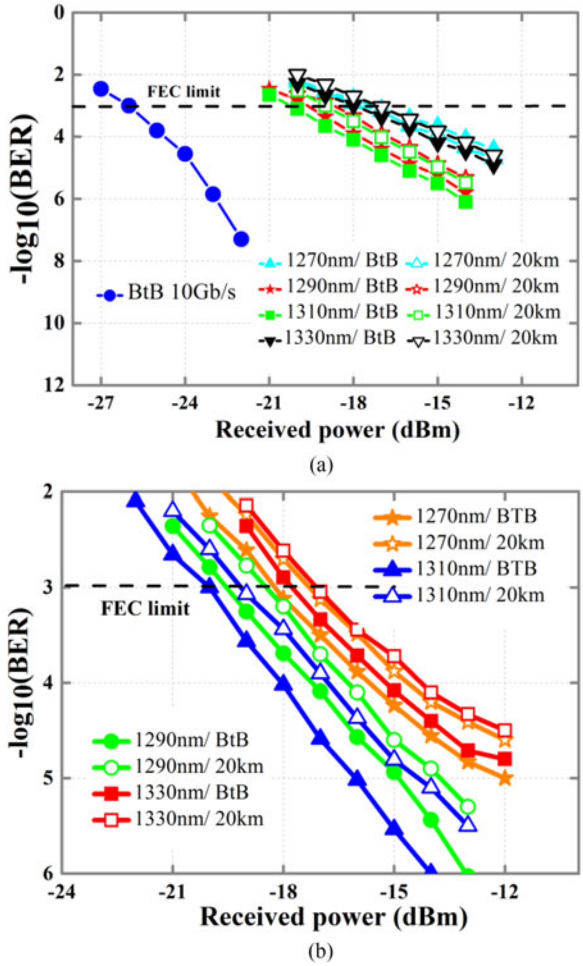


Fig. 7. Eye diagrams of 25.78-Gb/s NRZ-OOK signals at BtB and 20-km reach with and without DSF for 1270nm (A1-A4), 1290 nm (B1-B4), 1310 nm (C1-C4) and 1330 nm (D1-D4).

can clearly observe the signal quality improvement benefited from the frequency equalization effect of the DSE technique from Fig. 7 (A2), (B2), (C2), (D2). Besides, the performance is slightly worse for 1270 nm and 1330 nm channels due to the dispersion value of DSF is not the optimal in both cases. After 20-km SSMF transmission, the. phenomenon is similar with the BtB case since the dispersion of SSMF is near to zero at O-band. Note that the 20-km SMF will also introduce an amount of negative dispersion at 1270 nm Therefore, the eye diagram of the signal at 1270 nm will also slightly open after 20-km SMF transmission without DSF. As for upstream, we employ the same DSF to equalize the bandwidth. Therefore, the eye diagrams evolution for upstream signal is similar with the downstream one.



(a)

(b)

Fig. 8. BER measurement results for 4 downstream channels (a) and 4 upstream channels (b) at BtB and 20-km reach with DSE function.

B. *BER Performance*

We set up an experiment to investigate the whole TWDM-PON system BER performance. We test the BER performance for both downstream and upstream signals at BtB and 20-km reach. For both upstream and downstream, the BER are measured by a CDR chip embedded BERT. Besides, the PRBS data sequence is set at $2^{31} - 1$ and the BER results are shown in Fig. 8. As mentioned before, the optimal operating current of each DML is 44.35 mA with 8 dBm output power. However, for downstream direction, the launch power into the SMF is only -4 dBm per wavelength due to the insertion loss of passive optical components and DSF. Without the DSF, we cannot measure the BER since the CDR chip is out of lock due to very bad signal quality. After being equalized by the DSF, the eye diagrams are all open with a sensitivity of between -20 dBm and -17 dBm for all channels at BtB. The penalty variations at BER of 1×10^{-3} are within 1 dB for all channels after 20-km SMF transmission. The performance of 1290 nm and 1310 nm channels is the best, which can achieve -19 dBm sensitivity at 20-km reach. As for the channels of 1270 nm and 1330 nm, the sensitivity is 2 dB worse since they can generate negative and positive dispersion in the SSMF transmission, which is away from the optimal negative dispersion value of the DSE function. If the channel spacing of 800 GHz around 1310 nm is adopted as the wavelength plan, the performance of all channels will be almost equivalent. We also measure the system BER performance at 10-Gb/s without DSF for reference with a sensitivity of around -26 dBm. For the 25.78-Gb/s upstream signal, we employ the same DSF to improve the bandwidth. The transmission performance at BtB and 20-km are shown in Fig. 8(b). The receiver sensitivity can also achieve -19 dBm at 1310 nm. It is noted that the launch power of the transmitter in the ONU side is 8 dBm. Thus, the upstream link loss budget can achieve 27 dB after 20-km SMF transmission. However, considering the insertion loss of passive components and 20 km SMF, there is no much left for power splitter to support more users for both upstream and downstream. Therefore, an O-band SOA is required to compensate the insertion loss and improve the loss budget.

C. *SOA for Loss Budget Improvement*

To further improve the system loss budget, we employ a SOA to boost the optical power before being launched into fiber for the single-wavelength or four-wavelength case. We investigate the dependence of the required power for a BER of 1×10^{-3} on

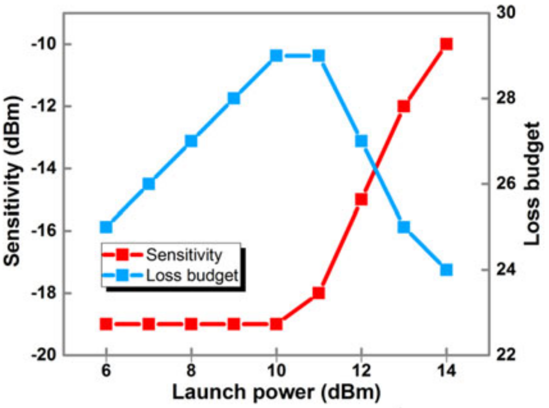


Fig. 9. Sensitivity of downstream signal at BER of 1×10^{-3} as a function of SOA launch power into the 20-km SMF.

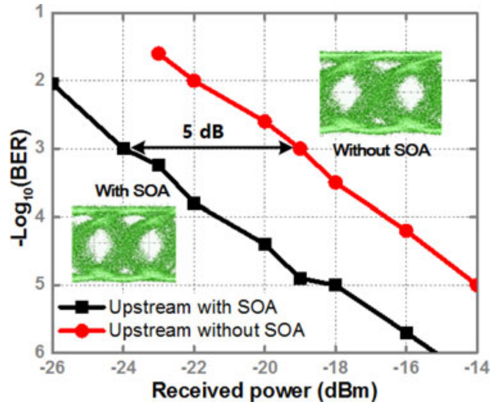


Fig. 10. BER versus received power for with and without SOA as pre-amplifier.

the SOA launch power for 20-km SMF downstream link. The results are shown in Fig. 9. The signal generated by DML is more tolerant to fiber nonlinearity. Therefore, the launch power can achieve 10 dBm. The highest loss budget for single channel case is 29 dB at 10 dBm launch power of DS channel. As the four wavelengths coexist in the fiber, the receiver sensitivity of one of the four channels starts to degrade when the power launched into the fiber is more than 13 dBm, corresponding to 26 dB loss budget. Therefore, when four wavelengths coexist in the fiber, the performance will be degraded by the high launch power induced nonlinearity.

As for upstream, we propose to use the same SOA as pre-amplifier to compensate the power loss of SMF and DSF. Note that even the SOA is a bidirectional amplifier, the BER measurement for downstream and upstream is separate due to the nonlinearity induced distortion will degrade the signal performance if we amplify the both upstream and downstream signals simultaneously. We vary the receiver power into the SOA using a VOA and keep the injection power into the APD fixed at −10 dBm by adjusting the gain of SOA during the sensitivity measurement. We compare the BER performance for 25.78-Gb/s signal after 20-km fiber transmission with and without SOA for one channel at 1310 nm. The results are shown in the Fig. 10. The signal quality shows no obvious degradation after employing SOA to compensate the DSF loss as the inset eye diagrams show. And the receiver sensitivity is changing from −19 dBm to −24 dBm with 5 dB improvement after employing SOA. From the view of cost, a PIN can be used to replace APD as upstream detector since the high-gain SOA is used for upstream. Considering the 8 dBm launch power of DML, the US loss budget can be as high as 32 dB. The detailed US and DS loss budgets of 1310 nm channel with SOA are shown in Table I. Note that power fluctuation and pattern effect caused by burst-mode upstream signal can be compensated by a limited amplifier using a gain saturated SOA with an inverted-mode signal [22].

TABLE I
LOSS BUDGET EVALUATION

	Output Power	Sensitivity @1e-3	Loss budget
Downstream	7 dBm	-19 dBm	26 dB
Upstream	8 dBm	-24 dBm	32 dB

V. CONCLUSION

To the best of our knowledge, we have demonstrated the first symmetric 100-Gb/s TWDM-PON with 4 × 25-Gb/s capacity on both downstream and upstream directions operating in O-band using NRZ-OOK format. A spool of DSF in OLT is used to equalize the frequency response of the transceivers therefore enables 25-Gb/s NRZ-OOK directly detection based on 10Gbps DMLs and APDs without DSP. The system loss budget is greatly improved by using SOA-based booster/pre-amplifier. Since the DSF is wavelength-insensitive and can be shared by all users, the proposed DSE technique would be a practical and low-cost solution for symmetric 100G-PON.

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