Symmetric 40-Gb/s, 100-km Passive Reach TWDM-PON with 53-dB Loss Budget

Zhengxuan Li, Lilin Yi, Wei Wei, Meihua Bi, Hao He, Shilin Xiao, and Weisheng Hu

***Abstract*—A truly passive long-reach, symmetric 40-Gb/s time and wavelength division multiplexed passive optical network (TWDM-PON) with a high loss budget is demonstrated, using direct modulation and direct detection in both upstream and downstream directions. Thermally tuned directly modulated lasers (DMLs) are employed to serve as both upstream and downstream transmitters, not only owing to their low cost, but also, as a carrier-less modulation method, where the signal generated by direct modulation is demonstrated to be more robust to high launch power induced fiber nonlinearities compared with external intensity modulation formats with strong carrier power. Therefore, DML is suitable for applying in TWDM-PON to achieve a high loss budget. Moreover, the frequency chirp induced dispersion of directly-modulated signal is managed thanks to the combination of optical spectral reshaping and dispersion supported transmission effects, which makes it possible for the directly-modulated signal to reach a distance of 100 km and still with a good quality. As a result, a system loss budget of 53 dB is achieved, supporting more than 1000 users with 100-km purely passive reach, which is the first demonstration of high loss budget, long reach TWDM-PONs to our best knowledge.**

***Index Terms*—Directly-modulated laser (DML), dispersion supported transmission (DST), long reach, loss budget, time and wavelength division multiplexed passive optical network (TWDM-PON).**

I. INTRODUCTION

THE invention of Internet provides us entertainments and convenience in the past few decades. And with the endless emergence of fresh new applications, such as online video/audio, high definition television, large files downloading and online games etc., the bandwidth requirement of each subscriber is increasing continuously. With the rapid development of optical communications industry, optical access network (OAN) is now able to provide high bandwidth with low cost, which has replaced the traditional copper access and became the mainstream access method. Driven by the increasing bandwidth demand, the capacity expansion of OAN never stopped. The capacity of the first generation Ethernet passive optical network and Gigabit-capable PON is 2.5/1.25 and 1.25/1.25 Gbps respectively. After that, XG-PON is proposed with a capacity of 10 Gb/s, also named as next generation PON stage 1 (NG-PON1). In recent years, the requirement for establishing next generation PON stage 2 (NG-PON2) was brought up. Lots of recommendations on network structure were proposed, including time division multiplexing PON, wavelength division multiplexing PON (WDM-PON), time and wavelength division multiplexing PON (TWDM-PON) and orthogonal frequency division multiplexing PON etc. Taking advantage of the backward compatibility and technical maturity, wavelength stacked TWDM-PON won out and was selected by full service access network as the primary architecture for NG-PON2 in Apr. 2012. Afterwards, standards such as G989.1 and G989.2 were formulated by ITU-T, which defined the requirements of NG-PON2, including system capacity, wavelength plan, loss budget and reach distance etc [1].

Several research groups have reported their system proposals and experimental results on NG-PON2. Huawei has demonstrated the world-first 40/10-Gb/s TWDM-PON prototype with 38-dB loss budget, where directly modulated laser (DML) was used as upstream laser source with on-off-keying (OOK) format [2], [3]. However, in recent years, with the popularity of new applications such as IPTV, online video chatting and massive multiplayer online games etc., the peer-to-peer traffic proliferates as a result, which raises the demand for upstream bandwidth and calls for capacity upgrading in PON systems. Therefore symmetric data rates might be preferred in the long run, i.e., the capability of symmetric 40-Gb/s data rate is required for future TWDM-PON. For symmetric 40-Gb/s system, in order to mitigate the dispersion penalty, spectral-efficient formats including duo-binary and four-level pulse amplitude modulation were used to drive the DML, where 20-km fiber transmission was realized, but after 40-km transmission, the penalty became unacceptable [4]. We have demonstrated a symmetric 40-Gb/s system with 40-km reach and 39-dB power budget by using optical spectral reshaping to mitigate the frequency-chirp induced dispersion [5], [6], which has already satisfied the capacity and distance requirements of NG-PON2. However, with the advanced optical technologies, the span can be further increased to 100 km or higher, which is known as long reach PON (LR-PON) [7]. With the wider coverage, LR-PON is expected to provide service for a large number of customers in the access/metro area with a decreased capital and operational expenditures. Both long distance transmission and high splitting ratio result in high link loss therefore the loss budget is a key parameter for a long-reach PON. Even though electrical or optical repeaters in the remote node can improve the transmission distance and loss budget [8]–[10], truly passive reach is

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The authors are with the State Key Lab of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: antlzx@sjtu.edu.cn; lilinyi@sjtu.edu.cn; weiweimmc@126.com; bmhua2006@gmail.com; hehao@sjtu.edu.cn; slxiao@sjtu.edu.cn; wshu@sjtu.edu.cn).

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preferred in order to keep the "passive" characteristic of PON system. External modulation combined with coherent detection has been considered as a good solution for long reach and high loss budget [9], [10]. Using complex modulation format and coherent digital receiver in optical line terminal (OLT) and/or optical network unit (ONU), symmetric 10G-PON with loss budget up to 53 dB [11] and 51 dB [12] (considering the FEC limit BER of 3.8×10^{-3}) have been achieved. But for commercial applications, it's more attractive if the less complicated technique—direct modulation and direct detection (DM-DD) can achieve the same performance [13]. For such a DM-DD TWDM-PON, the choice of upstream laser source is a challenge, which must be capable of carrying 10-Gb/s signal and keep it in good quality even after 100-km fiber transmission, be colorless and cost-effective as well. Colorless laser source has been discussed a lot in WDM-PON, where self-seeding or injection locked RSOA/FP-LD [14], [15] are good candidates to obtain a cost-effective laser with a wide tuning range. But in TWDM-PON, only a few channels are required, therefore a laser source with several nanometers wavelength tuning range is sufficient. Wong *et al*. have proposed to use short cavity vertical cavity surface emitting laser as upstream laser source and realized $8 \times 10\text{-Gb/s}$ aggregate upstream capacity [16]. J. Jenson *et al*. investigated the application possibility of VCSEL in coherent PONs [17]. Both have verified the feasibility of using VCSEL as upstream transmitter in TWDM-PON. Similar with VCSEL, directly modulated distributed feed-back (DFB) laser with higher output power is another potential choice. However, it is well-known that the laser generates strong frequency chirp when being modulated at high data rate, which will interact with chromatic dispersion in fiber and severely distort the signal during fiber transmission. Generally, optical or electronic dispersion compensation is required to recover the distorted signal. We have demonstrated that using delay interferometer (DI) based optical spectral reshaping combined with dispersion supported transmission (DST) effects, 100-km passive reach can be realized when DML is used as upstream laser source [13].

For the downstream laser source selection, the fiber nonlinearity tolerance is of critical importance for enabling high launch power therefore high loss budget. We made a comparison of several laser sources by evaluating their tolerance to high launch power, including laser with external modulation, electro-absorption modulated laser (EML), DML and chirp managed laser (CML). Experimental results verified that owing to their carrier-less and wide-spectra features, signals generated by DML and CML are more robust to high launch power induced fiber nonlinearity [18]. Therefore they are more suitable to be applied as downstream laser sources in high loss budget situations.

As for the loss budget improvement, instead of adding repeaters in the remote node, we employed amplifiers in terminals to keep the system passive. In the OLT, we used L-band high power erbium-doped fiber amplifier (EDFA) to boost the downstream signal power and C-band hybrid Raman/ EDFA to improve the sensitivity of upstream signal; while in the ONU side, an semiconductor optical amplifier (SOA) was used to improve the downstream signal sensitivity because it's of small size and suitable for integration. In this paper, taking advantage of the high nonlinear tolerance and long-reach supportive character of directly modulated signal, and with the help of terminal amplification, optical spectral reshaping and DST effect, we demonstrated a high loss budget, long-reach TWDM-PON system using CML and DML as downstream and upstream transmitters respectively. A capacity of symmetric 40-Gb/s and a loss budget of 53 dB are achieved, which could support 100-km standard single mode fiber (SSMF) transmission and more than 1000 users.

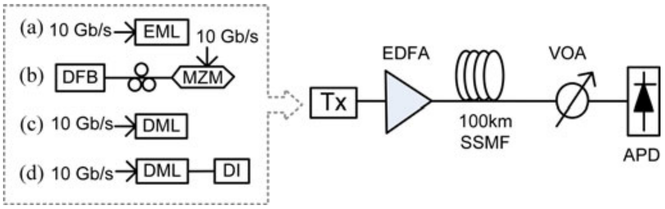


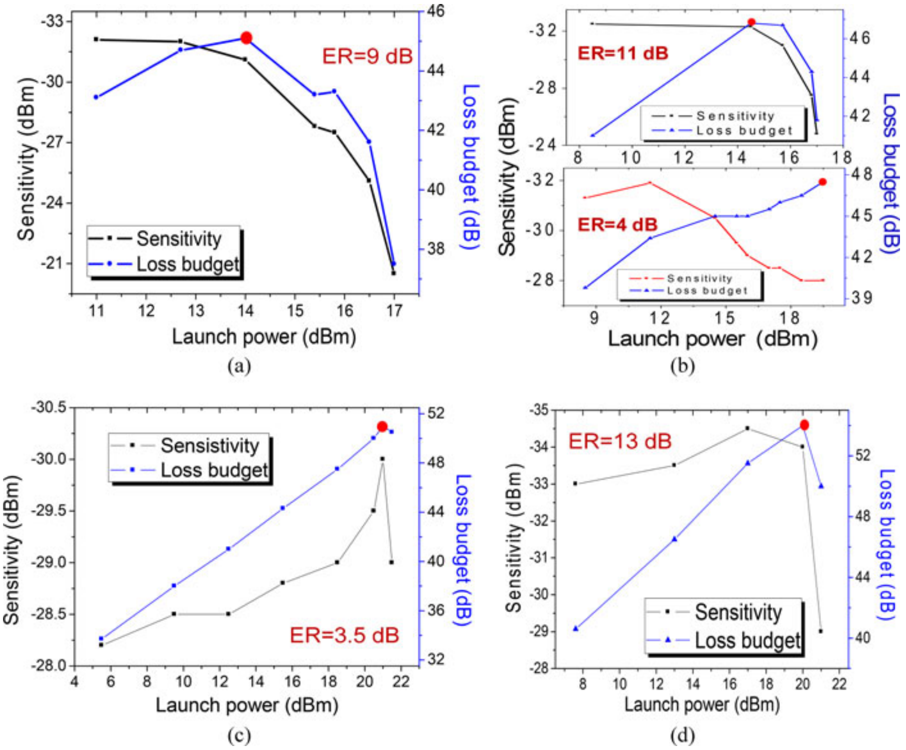
Fig. 1. Experimental setup for transmitter comparison.

The manuscript is organized as follows: in Section II, we evaluated the performances of different laser sources and explained the reason of choosing DML in our system; in Section III, we proposed a DM-DD technique based symmetric 40-Gb/s TWDM-PON system and evaluated its performances; Section IV concludes the paper.

II. CHOICE OF LASER SOURCE

The loss budget of a system is determined by two factors: the launch power and receiver sensitivity. However, the launch power is always limited because of the nonlinear effects in fiber, such as stimulated Brillouin scattering (SBS), self-phase modulation (SPM) etc., which will distort the signal severely as long as the power exceeds the thresholds. In most of previous long reach 10G-PON demonstrations, external modulation using Mach–Zehnder modulator (MZM) or EML were considered with superior performance compared with the DML case. But from the viewpoint of high launch power, the signal generated by DML is expected to have higher tolerance than others. The prediction comes from the fact that for high launch power scenario, SBS is an important nonlinear impairment. Both EML and MZM based OOK formats have a strong carrier component in their optical spectra, which can easily reach the SBS threshold and cause signal distortion. Inversely, the optical spectrum of DML is carrier-less and wide, which make it especially suited for high launch power applications. In order to verify this point, we made a comparison among several commonly used transmitters, including DFB laser combined with MZM, EML and DML. Except for SBS, there are other factors that can impact the results, such as SPM, which is another significant factor that impairs signal when the pulse peak power is high. Signal with a low extinction ratio (ER) has superiority in this respect because the "1" level has a relatively lower power than in high ER case. Besides, we should pay attention to fiber dispersion caused signal impairment in long reach transmission.

The comparison among transmitters was carried out under 100-km SSMF transmission case. Fig. 1 depicts the



(a) (b) (c) (d)

Fig. 2. Sensitivity of downstream signal at BER of 3.8e-3 as a function of launch power using (a) EML (b) OOK modulation using MZM (c) DML and (d) CML as transmitters.

experimental setup. Four 10-Gb/s transmitters are involved for comparison, including EML, MZM, DML and DML followed by a DI to imitate CML. Since we do not have EML operating at L+ band as the TWDM-PON standard requested for the downstream wavelength, all the transmitters are operating at ∼1542nm for fair performance comparison. 10-Gb/s PRBS data with a word length of 2^{31}–1 intensity-modulated the transmitters to get OOK signal outputs. Differential phase-shift-keying (DPSK) and duo-binary formats generated by MZM are also carrier-less, but they are not in the scope of comparison due to higher cost. An EDFA with an output power up to 23 dBm was used to control the power before launching into the fiber. After 100-km fiber transmission, the signal passes through a variable optical attenuator (VOA) for power attenuation and then launched into an APD for detection.

Fig. 2 shows the experimental results in terms of receiver sensitivity as a function of launch power. The corresponding loss budget is also calculated and shown in the figure. The sensitivity in this paper refers to the power received by the APD when the bit error rate (BER) is 3.8×10^{-3}. The measured results are in good agreement with the previous predictions. Note that the objective of this measurement is to find the highest loss budget for different transmitters therefore we did not compare the performance under the same ER. For EML based transmitter with 9-dB ER, the sensitivity falls down rapidly when the launch power exceeds 14 dBm, resulting in a highest loss budget of 45 dB as marked in Fig. 2(a). The similar results are observed in MZM case when the ER is 11 dB as shown in the upper section of Fig. 2(b). By adjusting the Vpp of the driven signal on the MZM, we can obtain a signal with lower ER, which means a smaller pulse peak power. The lower part of Fig. 2(b) shows the results when the ER is 4 dB, from which we can see a gentler decreasing slope than the 11 dB case, corresponding to a highest loss budget of 47.5 dB. But when we turn to DML and CML based transmitters, the situation is much different, as shown in Fig. 2(c) and (d). It's generally acknowledged that DML is unsuitable for high data rate, long distance fiber transmission due to the strong frequency chirp. The chirp broadens the optical spectrum and distorts signal during fiber transmission due to the chromatic dispersion. However, when the fiber is long enough, the fiber dispersion will firstly distort the signal and then convert the frequency modulation into intensity modulation therefore increasing the ER, which is known as DST technique [19]. Also, the low ER ($2 \sim 3$ dB) of the signal makes it more robust to SPM effect, which is quite suitable for high launch power application. The measured results of DML under various launch powers are shown in Fig. 2(c). We can see that due to the interaction between SPM and dispersion, the sensitivity was improved with the increase of launch power until the launch power exceeds 21 dBm, providing a highest loss budget of 51 dB. Apart from DST, spectral reshaping filter is more widely used to improve the transmission performance of DML, which is also known as CML [20]. By narrowing down the optical spectrum as well as increasing the ER, higher dispersion tolerance is obtained, which allows for long distance transmission. Similar with DML, the carrier-less spectra show higher tolerance to SBS effect. But as the ER is enhanced to ∼10 dB, the SPM effect is stronger. The sensitivity decreases at a lower

TABLE I
SUMMARY OF TRANSMITTER PERFORMANCES OPERATING AT 1543 nm

Transmitter	Maximal launching power (dBm)	Sensitivity (dBm)	Loss budget (dB)	Split ratio	Margin (dB)
EML	14	−31	45	256	1
MZM (ER = 11 dB)	16	−31	47	512	0
MZM (ER = 4 dB)	19.5	−28	47.5	512	0.5
DML	21	−30	51	1024	1
DML + DI (CML)	20	−34	54	2048	1

launch power of 20 dBm as shown in Fig. 2(d). Note that for all the transmitters, when the launch power exceeds 22 dBm, the signals are so severely impaired that we cannot get a BER lower than 3.8×10^{-3}. Table I gives a summary of the results, where DML and CML based transmitters provide a higher loss budget than the other transmitters. So it can be concluded that for large-split, long-reach PONs, DML and CML outperform other transmitters. MZM and EML based transmitter with low frequency chirp have been considered as good candidates for long-haul and metro applications. But from both performance and cost viewpoints, DML and CML are better choices in long-reach PON applications according to the above measurement results.

As L+ band is assigned for downstream transmission in NG-PON2, we also made a comparison among DML, CML and MZM in L+ band. As the dispersion parameter of the fiber on L+ band is different from the C band, also the chirp parameter of the L+ band DML is different from the C band one; the DST effect itself doesn't offer a clear eye opening after 100-km fiber transmission. The 100-km transmission must rely on the optical spectral reshaping filter, i.e. CML is required for downstream transmission in NG-PON2. The receiver sensitivity of the CML operating at L+ band is ∼4 dB worse than that of the C band case. The loss budget provided by the L+ band CML is ∼50 dB, which is still much better than the external modulation case. Thereby CML was chosen as the downstream transmitter in our high loss budget PON system demonstration. The performance of the downstream laser source will be further investigated in the following section.

For the upstream direction, with the help of DST, DML can be used as a cost-effective upstream laser source. The tunability of DML was also evaluated, as we tune the operating temperature, the output wavelength changes accordingly. During 60 °C temperature tuning range the output wavelength varies from 1541.8 to 1544.5 nm for the C-band DML and from 1604.3 to 1607 nm for the L-band one, with a stable output power of ∼10 dBm, which is sufficient for four channels separated by 0.8 nm. The output spectrum is shown in Fig. 3. As the upstream transmission of DML relies on DST effect, the quality of the signal is dependent on the transmission distance. Therefore we need to investigate the distance-dependent performance.

We investigated the sensitivity of the both the downstream and upstream signals under various transmission distance cases. For downstream direction, the evaluation was carried out using CML with a launch power of 20 dBm and operating wavelength of ∼1605 nm. As for the upstream link, the transmitter is a DML operating at ∼1542 nm with a launch power of 10 dBm.

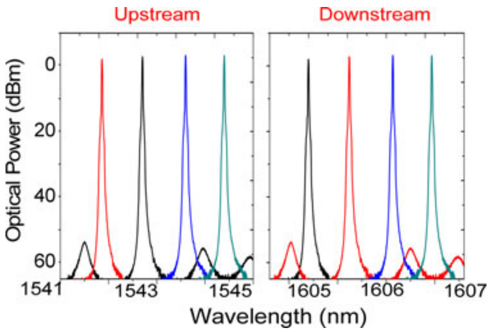


Fig. 3. Tuning ability of the DML with temperature.

We measured the eye diagrams and the sensitivities of the signal in both directions when the transmission distance varies from 0 to 100 km with an increasing step of 25 km. The results are shown in Fig. 4. For CML, we can see gentle sensitivity degradation with the increase of transmission distance, which can well handle the reach difference. For the DML, the eye diagram was firstly distorted during fiber transmission and then became clear again after propagating 75 km. We have proved that the distance can extended to more than 165 km and still with a clear eye opening [18], which coincidences with the DST theory [19]. Therefore DML can well support long distance transmission. For the short distance case, although the sensitivity is low, the split ratio can also be as high as 1:1024 because of the lower transmission loss of the shorter fiber link. To further improve the upstream performance, we can use an optical filter in the receiving end to remove the residual chirp [6]. In this way, we can obtain a clear eye diagram under any transmission distances. The sensitivity of upstream signal can be improved by 19, 12, 7 and 2 in 25, 50, 75 and 100 km cases separately by using a DI at OLT, which are also shown in Fig. 4(b).

Taking the experimental results demonstrated above, we further confirmed the feasibility of using CML as downstream transmitters and DML as upstream transmitters in long reach, high loss budget TWDM-PON system. In the following section, we will present a system demonstration of a symmetric 40-Gb/s TWDM-PON with 100-km passive reach using the DM-DD technique.

III. SYMMETRIC 40-Gb/s TWDM-PON

A. *Experimental Demonstration*

Fig. 5 depicts the network configuration of the proposed repeater-less long reach TWDM-PON. The aggregate data rate

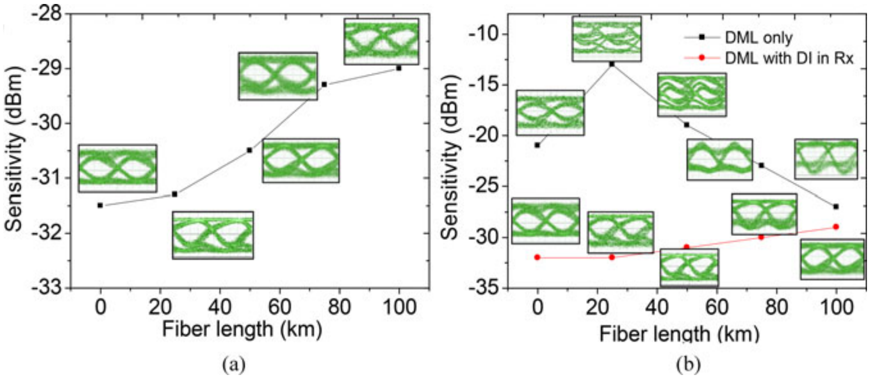


Fig. 4. Sensitivities versus transmission distance for (a) CML-based DS signal and (b) DML-based US signal w/ and w/o fiber end filtering.

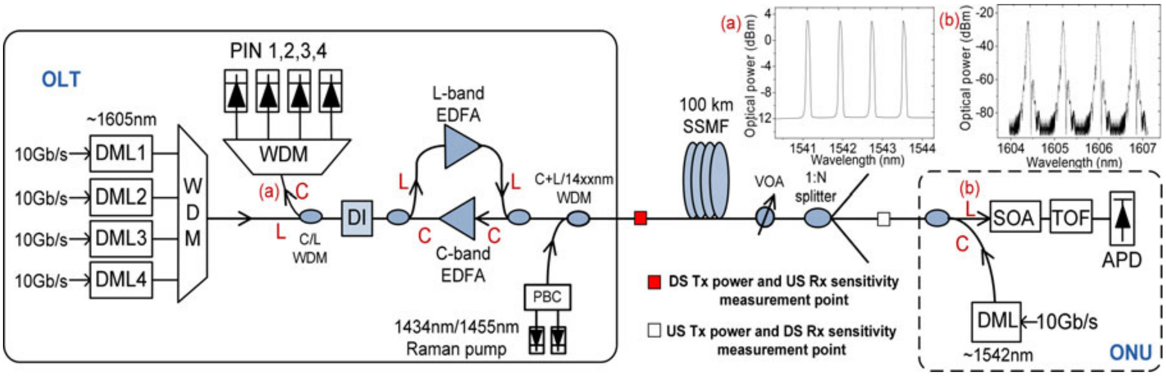


Fig. 5. Experimental setup of 100-km long reach, symmetric 40-Gb/s TWDM-PON.

of symmetric 40-Gb/s is achieved by stacking four pairs of wavelengths in both upstream and downstream directions. Four DMLs working at $\sim$1605 nm under room temperature are used as downstream transmitters. The DMLs are thermally tuned to four wavelengths separated by 0.8 nm. Instead of assigning one spectral reshaping filter for each DML, a single DI follows the WDM is applied as a notch filter to suppress the frequency chirp of all channels, which performs as a CML array but with much lower cost. For the US direction, the DMLs are operating at $\sim$1542 nm under room temperature. The DML in each ONU is tuned to one of the four channels. The output wavelengths are shown in the insets of Fig. 5. The long reach transmission is enabled by DST technique combined with spectral reshaping in the receiving end. By passing through the same DI in the OLT, the residual frequency chirp can be suppressed at the fiber end, therefore achieving clear eye opening even at the chirp-dominated transmission distance, as illustrated in the above section. Thanks to the bi-pass character of the DI, the dispersion for all users are managed therefore no dispersion compensation is required, which is simple and cost-effective for commercial applications. The dispersion management method has also been proved to be applicable for burst-mode data [6]. For loss budget improvement, a C-band hybrid Raman/EDFA in OLT is used to improve the receiver sensitivity for all upstream signals. For the downstream direction, an SOA is used in each ONU to pre-amplify downstream signal to enhance the receiving sensitivity. Note that the SOA can be replaced by an RSOA combined with an optical circulator to reduce the cost of each user [5]. C/L WDMs distributed in the transmission link enable the coupling and separation of US and DS signals.

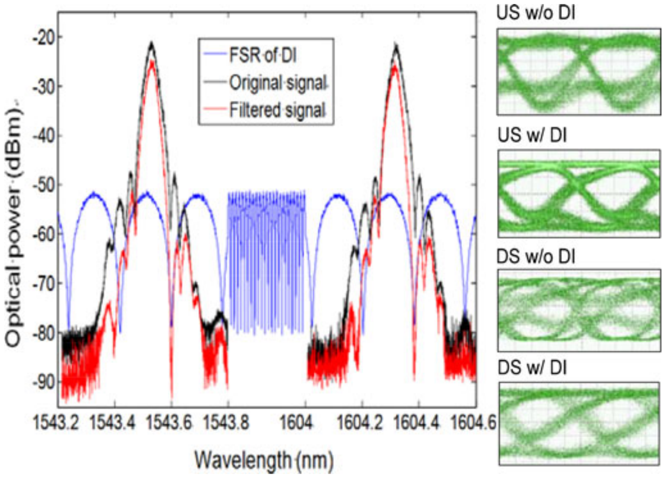
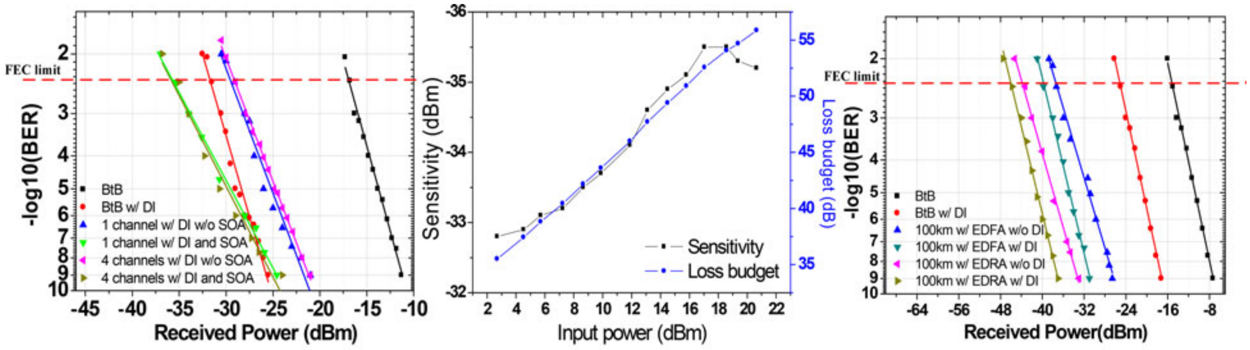


Fig. 6. Optical spectra and eye diagrams after 100-km fiber.

We set up an experiment to investigate the performance of the proposed TWDM-PON. In the DS direction, the multiplexed channels firstly pass through the DI for chirp management and then boosted by the L-band EDFA with a maximal output



(a) (b) (c)

Fig. 7. (a) BER measurement for DS signal (b) Sensitivity and loss budget variation with input power for DS single channel and (c) BER measurement for US signal.

power of 30 dBm before being launched into the fiber. The loss and chromatic dispersion of the 100-km SSMF is 20-dB and 2100 ps/nm respectively at 1605 nm. A VOA before the ONU is used to imitate the splitting loss. In the ONU side, an SOA amplifies all the four downstream channels firstly, then a TOF follows behind to select out the desired channel and suppresses amplified spontaneous emission power as well before the signal is launched into the detector. The SOA has an 18-dB gain and 7.5-dB noise figure (NF) at 1605 nm. A 10-GHz APD is used in each ONU to achieve high receiver sensitivity. For the US direction, the signal is firstly amplified by two Raman pumps, and then an EDFA with 45-dB gain and 3.9-dB NF at 1540 nm further amplifies the signal for sensitivity enhancement. By using two 250-mW pumps operating at 1434 and 1455 nm, the Raman amplifier provides a 10-dB small signal gain at 1540 nm. Compared with the optical or electrical extender solution at remote node, distributed Raman amplification solution by just adding Raman pumps and wavelength mux at OLT can keep the passive feature of the long-reach PON meanwhile reduce both the capital expense and operational expense [21], [22]. Then the signals pass through a DI for chirp mitigation. Finally a WDM demux directed all signals to four channels. A 10-GHz PIN is assigned in each channel to directly detect the desired US channel. For each DML, the modulated data are 10-Gb/s PRBS with a word length of 2^{31}–1. All the components used in this configuration are commercially available with mass production capability.

B. *Experimental Results*

Fig. 6 shows the optical spectra and eye diagrams of the original and reshaped signals of both directions after 100-km fiber transmission. The transmission character of the DI is also depicted. The DI (Kylia-WT-MINT) used in this experiment is a tunable DPSK demodulator, with a wide tuning range of its free-spectral range (FSR) from 10 GHz to infinite. As we tune the FSR from 10 to 100 GHz, we almost obtained the similar performances. In our experiment, we set the FSR at 25 GHz to support simultaneous operation of multi channels with 100-GHz spacing. The central wavelength of the DI is adjusted to suppress the long wavelength of the spectra, thereby suppressing the chirp corresponding to “0” levels and enabling long reach transmission. We can see the eye diagrams open clearly in both directions even after 100-km transmission. In practical applications, the wavelengths of the DMLs need to be well controlled to align with DI. We have investigated that +/−5GHz frequency drift is allowed. We measured the BERs and sensitivities of both directions and the results are shown in Fig. 7. As all four channels have the similar performance, we only take 1604.3 and 1543.5 nm for examples in DS and US directions respectively. Due to ER improvement, the use of DI can improve the back-to-back (BtB) sensitivity of DML from −17.5 to −31.5 dBm in the DS direction. The 100-km fiber transmission results in a power penalty of ∼2.5 dB, but the SOA can improve the sensitivity by 6 dB, so finally −35.2-dBm sensitivity can be achieved. Note that the SOA in our experiment is designed to operate in the C band. The sensitivity may be higher if a dedicated L-band SOA is used. Fig. 7(b) shows the sensitivity variation with the launch power of the DS single channel. The high power induced SPM benefits the sensitivity therefore the loss budget is improved with the input power increase. The highest loss budget for single channel is 55.9 dB at 20.7-dBm launch power. For four channels case, the maximal launch power is 18 dBm/ch, corresponding to 53.2-dB loss budget. With the further increase of the launch power, the strong SPM will severely degrade the signal thereby reduce the loss budget. When the total launch power is lower than 24 dBm, no interaction between different channels is observed. For the US direction, DI can improve the BtB sensitivity from −15.5 to −25.5 dBm by increasing the ER. After transmitting 100-km fiber, even without DI, the sensitivity can achieve −37.5 dBm with EDFA only due to DST effect. By using hybrid Raman/EDFA as preamplifier, the sensitivity is improved by 6 dB. The DI after the hybrid amplifier can further improve the sensitivity by 2.5 dB. As a result, a sensitivity of −46 dBm can be achieved, which is even better than the coherent receiver [12]. Considering the 10-dBm launch power of DML, the US loss budget can be as high as 56 dB. The detailed US and DS loss budgets are shown in Table II, where the loss of all other passive components has already been excluded.

The system loss budget of 53.2 dB is limited by the downstream direction where the launch power is limited by the cross phase modulation effect among different channels. Since the Raman pumps bring 6-dB sensitivity improvement for the

TABLE II
LOSS BUDGET EVALUATION

	DS		US	
	1 Ch	4 Chs	1 Ch	4 Chs
Tx power (dBm)	20.7	18	10	10
Rx sensitivity (dBm)	−35.2	−35.2	−46	−45.8
Fiber loss (dB)	20	20	20	20
Splitter loss (dB)	30	30	30	30
Total loss (dB)	50	50	50	50
Link budget (dB)	55.9	**53.2**	56	55.8
Margin (dB)	5.9	3.2	6	5.8

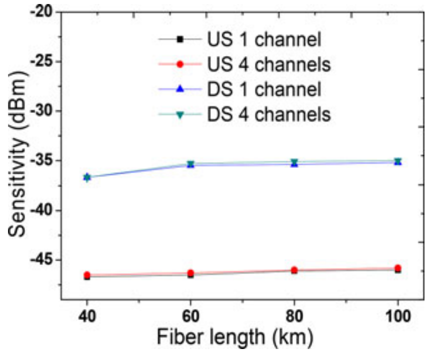


Fig. 8. Sensitivities under different transmission distances.

upstream link, the system loss budget will be decreased to 50 dB in case the Raman amplifier is restricted to be used in the system.

Finally, as the Raman gain is dependent on the transmission fiber, in order to verify that the proposed TWDM-PON is suitable for ONUs located at different transmission distances, the fiber length is varied from 40 km to 100 km with a step of 20 km. From Fig. 8 we can see the sensitivities of both DS and US signals are almost independent with the transmission distances since the EDFA can compensate the varied Raman gain. The residual Raman pump power at ONU is less than −20 dBm at 40-km distance, shows negligible effects on both US and DS performance.

IV. CONCLUSION

In this paper, we demonstrated a high loss budget, long reach TWDM-PON with a capacity of symmetric 40 Gb/s using DM-DD combined with terminal amplification. By comparing the performances of different laser sources under high launch power, CML is verified to be robust to high launch power and strong dispersion, which is well suited for downstream application. For the upstream link, DML is used because the DST effect in conjunction with end spectral reshaping enables the long distance transmission. A single DI at OLT reshapes the signal spectra of all channels for mitigating the dispersion. An L-band high power EDFA, a SOA and a C-band hybrid Raman/EDFA are used to increase the system loss budget to 53.2 dB, which could support 1024 users within a distribution range up to 100 km without any repeater. The proposed architecture provides a cost-effective solution for long reach and large split symmetric 40-Gb/s TWDM-PON.

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Authors' biographies not available at the time of publication.