Power budget improvement of symmetric 40-Gb/s DML-based TWDM-PON system

Meihua Bi, Shilin Xiao,[1,*] Lilin Yi,[1,2] Hao He, Jun Li,[1] Xuelin Yang,[1] and Weisheng Hu[1]

[1]*State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China*
[2]*lilinyi@sjtu.edu.cn*
**slxiao@sjtu.edu.cn*

Abstract: We propose a symmetric 40-Gb/s time and wavelength division multiplexed passive optical network (TWDM-PON) system with directly modulated laser (DML) as both downstream and upstream transmitters. A single bi-pass delay interferometer (DI), deployed in the optical line terminal (OLT), is used to mitigate multiple channels' signal distortions induced by laser chirp and fiber chromatic dispersion. With the help of the DI, we successfully demonstrate error-free transmission with the aggregate capacity of 40 Gb/s over different transmission distance. And in back-to-back case, by using a 0.2-nm free spectrum range (FSR) DI, ~11 dB optical power budget improvement is achieved at a bit error ratio of 1e-3. Owing to this high power budget, the maximum reach can be extended to 50 km for 1024 splits, 75 km for 256 splits, and 100 km for 64 splits. Meanwhile, the impacts of FSR of DI and laser wavelength shift on system performance are investigated in terms of receiver sensitivity. It is shown that, our system can achieve more than 43-dB power budget and support ± 2.5-GHz wavelength shift when the FSR is less than 0.2 nm.

OCIS codes: (060.2330) Fiber optics communications; (060.4250) Networks.

References and links

1. H. Nakamura, "NG-PON2 Technology," in *Proc. OFC* 2013, paper NTh4F.5 (2013).
2. D. Iida, S. Kuwano, J. Kani, and J. Terada, "Dynamic TWDM-PON for mobile radio access networks," Opt. Express **21**(22), 26209–26218 (2013).
3. C. W. Chow and C. H. Yeh, "Using downstream DPSK and upstream wavelength-shifted ASK for rayleigh backscattering mitigation in TDM-PON to WDM-PON migration scheme," IEEE Photon. J. **5**(2), 7900407 (2013).
4. N. Cvijetic, "OFDM for Next Generation Optical Access Networks," J. Lightwave Technol. **30**(4), 384–398 (2012).
5. S. Smolorz, E. Gottwald, H. Rohde, D. Smith, and A. Poustie, "Demonstration of a coherent UDWDM-PON with real-time processing," in *Proc. OFC*, 2012, Paper PDPD4.
6. K. Y. Cho, U. H. Hong, Y. Takushima, A. Agata, T. Sano, M. Suzuki, and Y. C. Chung, C. Keun Yeong, H. Ui Hyun, Y. Takushima, A. Agata, T. Sano, M. Suzuki, and Y. C. Chung, "103-Gb/s long-reach WDM PON implemented by using directly modulated RSOAs," IEEE Photon. Technol. Lett. **24**(3), 209–211 (2012).
7. Y. Luo, X. Zhou, F. Effenberger, X. Yan, G. Peng, Y. Qian, and Y. Ma, "Time and Wavelength Division Multiplexed Passive Optical Network (TWDM-PON) for Next Generation PON Stage 2 (NG-PON2)," J. Lightwave Technol. **31**(4), 587–593 (2013).
8. R. Murano and M. J. Cahill, "Low Cost Tunable Receivers for Wavelength Agile PONs," in *Proc.* ECOC 2012, Paper We.2.B.3.
9. Z. Li, L. Yi, M. Bi, J. Li, H. He, X. Yang, and W. Hu, "Experimental demonstration of a symmetric 40-Gb/s TWDM-PON," in *Proc. OFC* 2013, Paper NTh4F.3.
10. L. Yi, Z. Li, M. Bi, W. Wei, and W. Hu, "Symmetric 40-Gb/s TWDM-PON with 39dB Power Budget," IEEE Photon. Technol. Lett. **25**(7), 644–647 (2013).
11. P. P. Iannone, K. C. Reichmann, C. Brinton, J. Nakagawa, T. Cusick, E. M. Kimber, C. Doerr, L. L. Buhl, M. Cappuzzo, E. Y. Chen, L. Gomez, J. Johnson, A. M. Kanan, J. Lentz, Y. F. Chang, B. Palsdottir, T. Tokle, and L. Spiekman, "Bi-directionally amplified extended reach 40Gb/s CWDM-TDM PON with burst-mode upstream transmission," in Proc. OFC 2011, Paper PDPD6.
12. Y. Ma, Y. Qian, G. Peng, X. Zhou, X. Wang, J. Yu, Y. Luo, X. Yan, and F. Effenberger, "Demonstration of a 40Gb/s time and wavelength division multiplexed passive optical network prototype system," in *proc. OFC 2012*, paper PDP5D.7.

#200511 - $15.00 USD Received 1 Nov 2013; revised 9 Feb 2014; accepted 10 Feb 2014; published 18 Mar 2014

13. E. Wong, M. Mueller, and M. C. Amann, "Characterization of energy-efficient and colorless ONUs for future TWDM-PONs," Opt. Express **21**(18), 20747–20761 (2013).
14. E. Wong, M. Mueller, and M. C. Amann, "Colourless operation of short-cavity VCSELs in C-minus band for TWDM-PONs," Ele. Lett. **49**(4), 282–284 (2013).
15. M. Bi, S. Xiao, H. He, L. Yi, Z. Li, J. Li, X. Yang, and W. Hu, "Simultaneous DPSK demodulation and chirp management using delay interferometer in symmetric 40-Gb/s capability TWDM-PON system," Opt. Express **21**(14), 16528–16535 (2013).
16. J. L. Wei, C. Sánchez, R. P. Giddings, E. Hugues-Salas, and J. M. Tang, "Wavelength-Offset Filtering in Optical OFDM IMDD Systems Using Directly Modulated DFB Lasers," J. Lightwave Technol. **29**(18), 2861–2870 (2011).
17. C. R. Doerr, S. Chandrasekhar, P. J. Winzer, A. H. Gnauck, L. W. Stulz, R. Pafchek, and E. Burrows, "Simple multichannel optical equalizer mitigating intersymbol interference for 40-Gb/s nonreturn-to-zero signals," J. Lightwave Technol. **22**(1), 249–256 (2004).
18. B. Wedding, B. Franz, and B. Junginger, "10-Gb/s optical transmission up to 253 km via standard single-mode fiber using the method of dispersion-supported transmission," J. Lightwave Technol. **12**(10), 1720–1727 (1994).

1. Introduction

Driven by various new emerging high bandwidth services such as high-quality internet protocol TV (IPTV), online gaming, etc., the next generation passive optical network stage2 (NG-PON2) is currently being extensively explored [1–3]. To realize cost-effective, scalable and flexible the next generation passive optical network stage2 (NG-PON2), a lot of advanced techniques have been investigated [4–10], among which the time and wavelength division multiplexed passive optical network (TWDM-PON) proposal has attracted much research interest and has been selected by the Full Service Access Network (FSAN) as the base technology solution for NG-PON2 [7–10]. Nevertheless, how to reduce TWDM-PON system cost is also the primary challenge for carriers. As with any PON configurations, the cost reduction can be obtained by improving optical power budget (OPB), which is realized by increasing power splits or transmission distances [8]. Thus, high power budget and high subscriber rates are essential for deploying TWDM-PON system. So far, several potential solutions for TWDM-PON have been proposed [7–11]. Y. Luo et al. have demonstrated a TWDM-PON system with 40/10-Gb/s rates for down/uplink, achieving 38-dB OPB [7]. To satisfy the requirement of bandwidth-intensive services, the symmetric 40-Gb/s aggregated rates for TWDM-PON are considered as a new trend [9,10]. P. P. Iannone et al. [11] have proposed a symmetric 40-Gb/s coarse wavelength division multiplexed (CWDM)-TDM-PON system. A semiconductor optical amplifier (SOA) was installed in remote node (RN), which successfully extends the transmission distance but changes the deployed PON structure.

On the other hand, to reduce transceivers cost and inventory management of TWDM-PON, deploying high-speed colorless transmitters for both ends is considered as a promising solution [10,12–16]. The most common colorless transmitters in WDM-PON system, such as reflective SOA (RSOA) and Fabry-Pérot laser diode (FP-LD) which need the high-power stability seeding and external tunable reflecting filtered devices to achieve colorless feature thereby increasing the complexity of system. Meanwhile, due to their low modulation bandwidth (~2GHz), the FP-LD and RSOA need the electronic or optical equalization scheme to obtain more than 10-Gb/s data transmission, which will sacrifice the receiver sensitivities and power budget. Therefore, these colorless transmitters are not suitable for TWDM-PON system. The wavelength-tuned directly modulated lasers (DMLs) (such as distributed feed-back laser (DFB) and vertical cavity surface emitting laser (VCSEL)) [7,9,12–15] have been proposed as a potential colorless optical network unit (ONU) transmitter for TWDM-PON system due to its advantages of low cost, compactness, low insertion loss, relatively low driving voltage and high optical output power. These advantages make DFB ideal for optical access networks, both for the widespread deployment at user premises, as well as for implementation as central office sources. However, in high-speed DML-based system, the distortion caused by laser chirp and fiber chromatic dispersion severely limits the system performance [12–16]. To deal with this problem in DML-based TWDM-PON system, the specially designed tunable optical filter (TOF) is used to mitigate the distortions induced by chirp [9,10,13,15]. However, in our previous works [9,10], the specially designed filter has strict requirements on profile and bandwidth, and each wavelength channel needs an exclusive chirp managed filter, which increase the system cost and complexity. Moreover, we also have demonstrated a feasible scheme by employing delay interferometer (DI) in each ONU to process upstream signal chirp [15]. Although this scheme can achieve performance improvement, but it needs to deploy one DI with temperature control module for stabilizing the initial phase of DI in each ONU, which will increases the cost of ONU.

In this paper, we propose a symmetric 40-Gb/s TWDM-PON system employing low-cost DML as both upstream and downstream transmitters and a single bi-pass DI deployed in the optical line terminal (OLT) to mitigate the distortions of multiple bidirectional wavelength channels. With the help of DI, this scheme enhances the capabilities of system transmission distance and greatly improves OPB. The feasibility of proposed system is experimentally verified with different free-spectral range (FSR) of DI. Results show that, the system power budget depends on the FSR of DI and this system can support wide range of fiber transmission no matter the signal is severely or slightly distorted. Meanwhile, the system without repeater achieves 1:1024, 1:256 and 1:64 splitting ratio over 50 km, 75 km and 100 km fiber transmission respectively.

2. System architecture and experimental setup

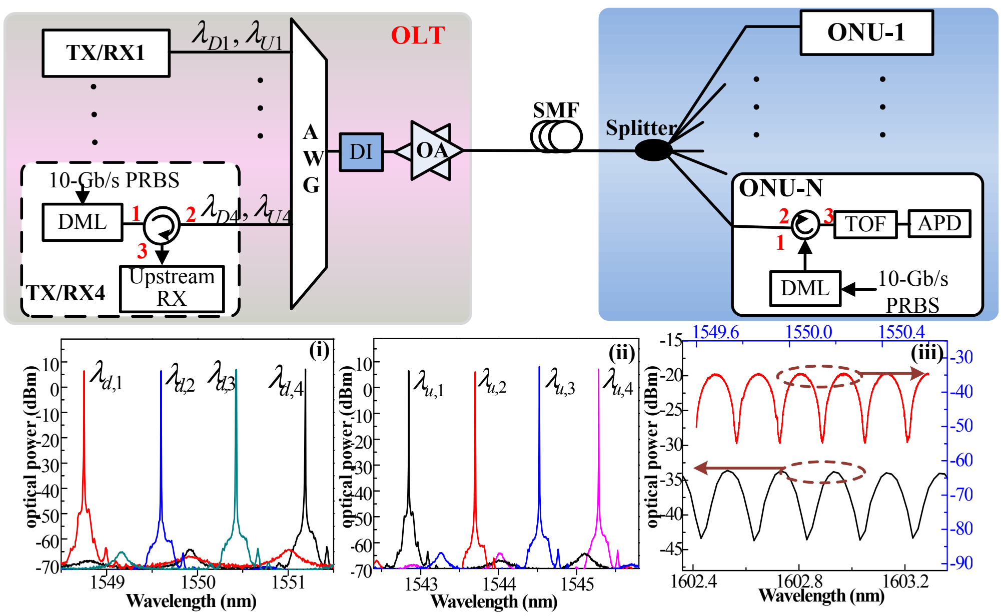

Fig. 1. Proposed TWDM-PON architecture, the inset (i) the spectra of the downstream channels, (ii) the spectra of the upstream channels, and (iii) the transmission spectrum of DI in the C-band wavelength and L-band wavelength.

The proposed TWDM-PON architecture is shown in Fig. 1, where four TDM-based PONs are stacked by an arrayed waveguide grating (AWG) with 0.8-nm channel spacing to achieve the symmetric 40-Gb/s aggregate rates. At the OLT, in each transmitter and receiver (TX/RX) unit, the commercially available low-cost directly modulated DFB laser is driven by 10-Gb/s pseudorandom bit sequence (PRBS) data with a word length of 2^{31}-1. Then, the signals are multiplexed by an AWG and are injected into a DI. After the AWG and DI, the signals are amplified to 13 dBm per wavelength by a bi-directional erbium-doped fiber amplifier (EDFA). Passing through the single mode fiber (SMF), the signals are distributed to each ONU by a splitter at the RN, and an optical attenuator is used to emulate the loss of optical splitter. Note that, the single DI installed in the OLT is used to mitigate the chirp-induced distortions for multiple bi-directional channels, which is different from the previous solution with a single chirp compensated device for each transmitter such as the chirp managed laser

(CML). Therefore, the cost of DI can be shared by all users of the system and becomes insignificant with the increase of users. Furthermore, the DI can be integrated into an AWG for cost reduction [17].

In each ONU, the downstream signals pass through a TOF with 0.8-nm bandwidth before being detected by an avalanche photo diode (APD). As for uplink, the DFB biased at 65mA has ~9-dBm stable output power with tunable wavelength range of ~3.0 nm, thus each ONU can be tuned among four wavelength channels with 0.8-nm spacing. After the power coupling and fiber transmission, the upstream signals are firstly injected into the bi-directional EDFA for pre-amplification and then into the DI for suppressing the distortion caused by the frequency chirp and dispersion. The filtered signals after DI are then fed into AWG and received by APD for upstream performance evaluation. It is worth noting that, since the specific wavelength plan standard for NG-PON2 is not ultimately defined yet and using the C-band wavelength can easily facilitate the co-existence with legacy PONs (GPON, XG-PON, and 10GEPON) [7,13], thus the upstream wavelengths in our experiment are set at 1541.71 nm, 1542.51 nm, 1543.31 nm and 1544.11 nm.

3. Experimental results

Firstly, we investigate the wavelength tuning feature of directly modulated DFB to enable colorless operation in TWDM-PON system. In this experiment, the directly modulated DFB is thermally tuned between 15°C to 65°C to generate four 0.8 nm-spacing wavelengths. Note that, using the similar wavelength plan as in [7,13], the downstream and upstream wavelength are selected as in the C-band, as demonstrated in inset (i) and (ii) of Fig. 1. At a bias current of 65mA, the output powers of DFB for eight-wavelength down/uplink are measured to be ~9 dBm. Compared to the current-biased tuned VCSEL [14], the output power of DFB is more stable and larger, increasing the launched power and the consistency of transmitter. Therefore, the same type of laser can be deployed in system, which can reduce the system inventory cost. These features make DFB be potential candidate for widespread deployment in TWDM-PON system, both for OLT and ONU.

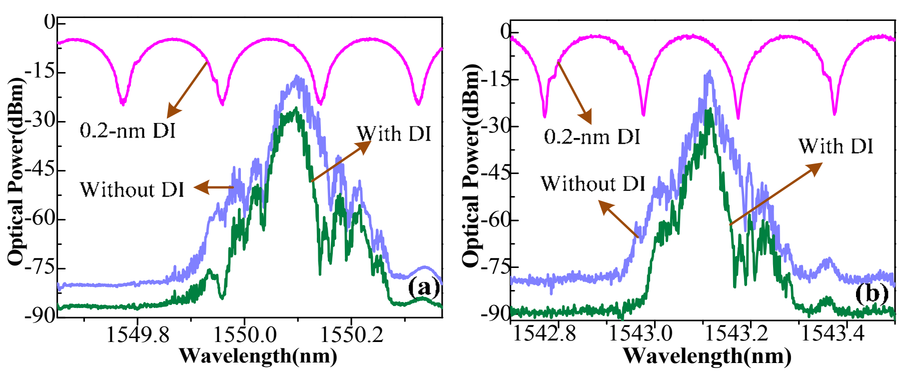

Fig. 2. optical spectrum of signal for 25-km SMF without and with the 0.2-nm FSR DI, and the DI transmittance spectrum in (a) downstream, (b) upstream.

In order to verify that the DI can be used to suppress the chirp of multiple transmitters, we investigate its property. The bi-pass characteristic of DI has already been demonstrated in our previous work [15]. In this paper, we further measure the transmittance curves and insertion loss in different waveband. The corresponding curves are depicted in inset (iii) of Fig. 1. It is observed that the DI has almost the same periodical transmittance profile in both C band and L band, and the corresponding insertion losses for two bands are measured to be ~3.86 dB and ~4.2 dB respectively. These results indicate that the DI has better periodicity and could support wide wavelength range, thus it can be used to process multiple wavelength channels even in different waveband.

#200511 - $15.00 USD Received 1 Nov 2013; revised 9 Feb 2014; accepted 10 Feb 2014; published 18 Mar 2014

The spectra of both downstream and upstream signals over 25-km SMF transmission with and without DI, and the transmittance curve of DI are shown in Fig. 2. Here, we use the DI with 0.2-nm FSR for simultaneous multi-channels operation with 0.8-nm spacing, and similar results can be achieved under other FSRs. By controlling the thermoelectric cooler (TEC) modules and electrically feed-back loop, the initial phase of DI is adjusted to a suitable place so that it can provide an optimum wavelength-offset with respect to the optical carrier. As shown in Fig. 2(a), the peak wavelength of DI transmittance curve is detuned ~0.04 nm to the short wavelength from the carrier. Thus, it can filter out the red shift chirp-induced spectrum broadening low-frequency components which is corresponding to the “0”s of data sequences, and hence increasing the extinction ratio (ER) of signals. Owing to the periodical notch property of DI, the partial noise floor of DML is also filtered out, therefore improving the signal to noise ratio.

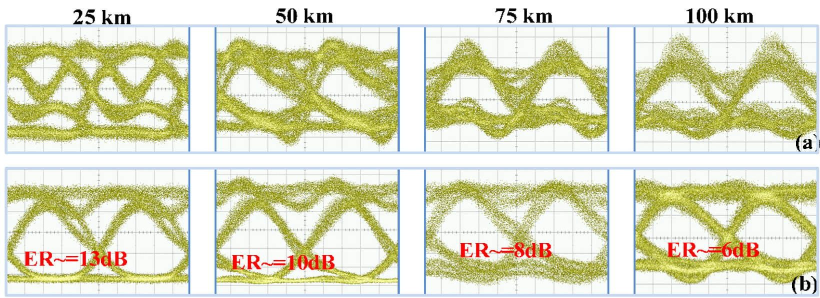

Fig. 3. measured upstream channel optical eye diagrams for various transmission distances (a) without and (b) with the DI.

Figure 3 depicts the upstream optical eye diagrams for different distances with and without the 0.2 nm-FSR DI. It is obvious that, without the DI, the eye diagram is firstly severely distorted and then becomes clear again over 50-km fiber and finally becomes bad again after 100-km transmission. This is caused by the fact that chirped signal interact with fiber chromatic dispersion, and as a result the signal distortions are smoothed out at the long distance transmission [18]. With the DI, no matter the eye diagram is completely or slightly closed, the clear and wide open eye can be recovered as shown in Fig. 3(b). Compared to the original signal with ~3-dB ER, the improvement ER of signal is measured to be 10 dB, 7 dB, 5 dB and 3 dB for 25 km, 50 km, 75 km and 100 km SMF transmission respectively. The similar results are also observed in downstream link, which are better than our previous work using the specially-designed TOF in [9,10].

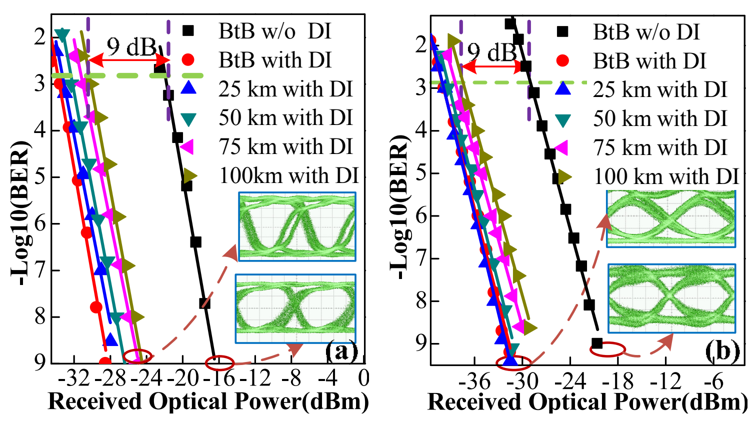

Fig. 4. measured BER with different fiber distance and electrical eye diagrams for (a) downstream and (b) upstream.

#200511 - $15.00 USD Received 1 Nov 2013; revised 9 Feb 2014; accepted 10 Feb 2014; published 18 Mar 2014

To study the transmission performance of this system, we measure the bit error ratio (BER) for down and uplink with and without DI as shown in Fig. 4. Both figures show the measurement values in the back-to-back (BTB) case, as well as in the cases of different fiber lengths. Since no obvious BER differences among the four channels for both directions, we only select the sensitivity under the worst case among four channels to analyze. Figure 4(a) depicts the downstream sensitivity with different transmission distance. The electrical eye diagrams of signal over SMF transmission with DI and BtB without DI are also shown in the inset of Fig. 4(a). It is obvious that the eye diagram with DI open more widely than that case without DI. Meanwhile, compared to the BtB case without DI, the sensitivity is improved by ~11dB, ~10.5 dB, ~9.5 dB, and ~9 dB at BER = 1e-3 over 25 km, 50 km, 75 km and 100 km fiber transmission, respectively.

The upstream BER and electrical eye diagrams with different fiber length are shown in Fig. 4(b). In comparison with the BtB case excluding DI, the receiver sensitivities at BER = 1e-3 are improved by ~11 dB, ~10.8 dB, ~9.6 dB and ~9 dB for 25 km, 50 km, 75 km and 100 km SMF transmission respectively, which results in significant OPB improvement. A little power penalty difference among the different distance is also observed from this figure, which can be attributed to different accumulated residual chromatic dispersion effect. In addition, it should be noted that, this DI-based scheme can be acted as a tunable dispersion compensator rather than a fixed dispersion one, and can support continuous length repeater-less fiber transmission. Thereby, it can be considered as a flexible and promising method for reducing the impacting of chirp on the DML-based TWDM-PON system. Meanwhile, due to the chirp properties of DML [16–18] and the periodical features of bi-pass DI, our scheme can support various data rate TWDM-PON system, and the corresponding work need to be further investigated.

Table 1. Comparisons of ER and Power Budget (at BER = 1e-3) Performance for Our Proposed TWDM-PON System

Different scheme	Scheme in this paper (25km)	Scheme in this paper (50km)	Scheme in this paper (75km)	Scheme in this paper (100km)	Scheme in [9] (25km)	Scheme in [10] (25km)	Scheme in [15] (50km)
ER w/o filtering	_____	~2 dB	~2 dB	~2 dB	_____	_____	~2 dB
ER with filtering	~13 dB	~10 dB	~8 dB	~6 dB	~5.6 dB	~7 dB	~13dB
power budget	**46.1 dB**	**45.3 dB**	**44 dB**	**43.2 dB**	**31 dB**	**39 dB**	**38 dB**
splitting ratio	1:1024	1:1024	1:256	1:64	1:256	1:1024	1:256

We also evaluate the maximum supported users of this system by calculating the OPB, and the corresponding results are shown in Table 1. Due to the DI installed just before the EDFA, no filtering loss is introduced for calculating the system OPB. The launched power is 13 dBm and 9 dBm for downstream and upstream link respectively. By the measured sensitivity with the worst case for both directions, we calculate OPB for the different transmission distance. As shown in Table 1, the OPB is ~46.1 dB, ~45.3 dB, ~44 dB and ~43.2 dB respectively for 25 km, 50 km, 75 km and 100 km fiber transmission, which supports 1:1024, 1:1024, 1:256 and 1:64 splitting ratios, respectively. Moreover, the comparisons of signals ER and power budget among our proposed TWDM-PON schemes are also demonstrated in the Table 1, where our proposed scheme in this paper achieves the highest power budget and ER.

4. Further discussion

To investigate the impact of the FSR of DI on TWDM-PON system, we use a DI with tunable FSR. Figure 5 shows the upstream sensitivity at BER = 1e-3 with the worst case among four channels for different fiber length without and with DI. It is shown that, for the excluding DI case, the sensitivity firstly degrades at 25-km SMF, then becomes better with the increase of fiber distance, and it is even up to ~-29 dBm over 75-km SMF. These results can be explained as the dispersion-supported transmission (DST) caused by the interaction of chirp with fiber dispersion [18]. Using the DI, it is evidence that the sensitivity is improved with different FSRs. Meanwhile, no matter what fiber length is, the sensitivity always decreases with the increase of FSR. The reason is explained as follows. From observations in the inset (i) of Fig. 5, as the FSR increases, the slope of DI transmission spectrum is not steep, leading to a poor spectral reshaping. It should be pointed out that, when the 0.1-nm and 0.2-nm FSRs are employed, almost the same performance is obtained, which means that 0.2-nm FSR DI is good enough for our system. The similar result is observed in the case of downlink.

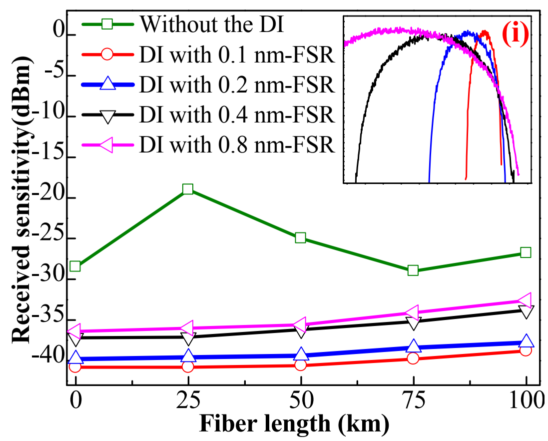

Fig. 5. measured upstream sensitivity at BER = 1e-3 versus the fiber length with the different FSR of DI, the insets (i) the DI transmission spectrum with different FSR.

We also investigate the influence of random wavelength shift of DML on system performance, and the results are demonstrated in Fig. 6. Since similar results can be observed in uplink and downlink, we only show the upstream receiver sensitivity penalties incurred by the DFB wavelength shift. Here, the zero frequency offset referring to the position that central wavelength of each passband in DI is located at ~0.04 nm off the laser frequency (as shown in Fig. 2), which corresponds to the position with the highest sensitivity. It is found that the sensitivity penalty increases with the increase of wavelength shift. The reason is attributed to weakly spectral reshaping. As for the same penalty, allowed wavelength shift range at BER of 1e-3 is larger than the case of BER = 1e-9. In addition, the frequency shift range in which the sensitivity penalty is below 3dB with BER = 1e-3 exceeds ± 2.5 GHz. Contrarily, when DML wavelength is fixed, around ± 2.5-GHz frequency shift of 0.2-nm FSR DI can be supported by this system. But, in practical systems, the temperature of DI can be stabilized by the TEC and the initial phase is electrically controlled with a feedback loop.

#200511 - $15.00 USD Received 1 Nov 2013; revised 9 Feb 2014; accepted 10 Feb 2014; published 18 Mar 2014

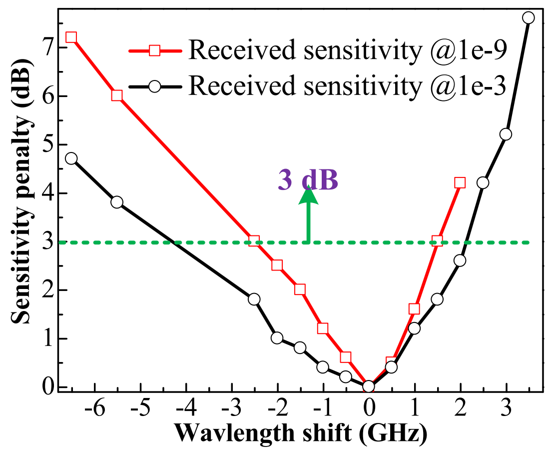

Fig. 6. Received sensitivity penalty versus the wavelength shift of DML with 0.2-nm FSR DI.

Finally, considering the factor of the FSR of DI, we get the whole system power budget as depicted in Fig. 7. It is clearly observed that, for a fixed FSR, an increasing fiber length brings in OPB reduction, resulting from the residual dispersion induced system degradation. An increasing in FSR also produces a low power budget due to the unfiltered chirp induced signal distortions. These two effects worsen the power budget and subsequently reduce the user numbers that the system can support. Thus, for a specific fiber length, a suitable FSR occurs, according to which a large power budget is observed. In addition, it can be seen in Fig. 7, for the FSR of < 0.4 nm, the minimum power budget of ~43 dB can be obtained for the fiber length of < 60 km, which supports at least 512 users. When the FSR <0.2 nm, we achieve the minimum power budget of ~43 dB over 100-km SMF and ~45 dB over 60-km SMF, which accommodate 64 users and 1024 users, respectively. From above analysis, it can be seen that the system power budget is adjustable when different FSR is adopted.

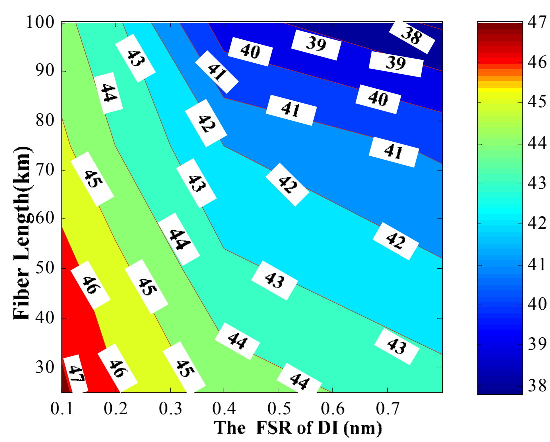

Fig. 7. Power budget of the proposed TWDM-PON system as a function of fiber length and the FSR of DI.

4. Conclusion

In this paper, we proposed a low-cost, high power budget, high system capacity, and legacy compliant system for future TWDM-PON. Through experiments, we demonstrated a symmetric 40-Gb/s DML-based TWDM-PON system using a single DI to mitigate the distortion caused by chirp and fiber dispersion. With a 0.2 nm-FSR DI, the reshaping spectra, the eye diagrams and BER with respect to fiber distances are investigated. Experimental results verify that, the ER of signal is improved by ~10dB for both downstream and upstream link by using the DI over 25-km SMF transmission, leading to ~11dB OPB improvement at BER = 1e-3. ~43 dB and ~44 dB OPB over 100 km and 75 km SMF are also obtained in our system, which could support 1:64 and 1:256 splitting ratios, respectively. Furthermore, the influences of different FSR of DI and the wavelength shift of laser on system performance are also studied. Corresponding results show that, for the FSR less than 0.2 nm, ± 2.5 GHz wavelength shift is allowed and large splitting ratio with different fiber length is achieved. Owing to its simplicity and excellent performance, the proposed architecture may be valuable for practical implementation in future TWDM-PON system.

Acknowledgments

The work was jointly supported by the National Nature Science Fund of China (No. 61271216, No. 61221001, No. 61090393 and No. 60972032), the National “973” Project of China (No.2010CB328205, No. 2010CB328204 and No. 2012CB315602), China Postdoctoral Science Foundation (No. 2013M540361) and the National “863” Hi-tech Project of China.