

# Upstream dispersion management supporting 100 km differential reach in TWDM-PON

Lilin Yi,<sup>1\*</sup> Xiaodong Wang,<sup>1</sup> Zhengxuan Li,<sup>1</sup> Jingqing Huang,<sup>2</sup> Jun Han,<sup>2</sup> Weisheng Hu<sup>1</sup>

<sup>1</sup> State Key Lab of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, 800 Dongchuan Rd, Shanghai, 200240, China

<sup>2</sup> II-VI Network Solutions, Shanghai, 200233, China

\*lilinyi@sjtu.edu.cn

**Abstract:** An optical dispersion compensator (ODC) with negative dispersion value in optical line terminal (OLT) is proposed to manage the chromatic dispersion of 10 Gb/s upstream directly-modulated signals from users with 100 km differential distances, achieving a maximal 51.9 dB loss budget thanks to the positive chirp of the directly-modulated signals and the characteristics of access networks that lower loss budget is required for the users at shorter transmission distance. The optimal dispersion value of the ODC is determined by the maximal distance of the users and the objective is to guarantee the loss budget monotonically improved with the increase of reach, therefore supporting differential reach. Experimental results show that it is a potential solution for practical implementation of long-reach and high splitting-ratio time and wavelength division multiplexed passive optical network (TWDM-PON).

©2015 Optical Society of America

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

---

## References and links

1. D. Mahgerefteh, Y. Matsui, X. Zheng, Z. F. Fan, K. McCallion, and P. Tayebati, "Chirp Managed Laser (CML): A compact transmitter for dispersion tolerant 10Gbps networking applications," presented at the *Optical Fiber Communication Conference (OFC)*, Mar. 2006, Paper OWC6.
2. L. Yi, Z. Li, M. Bi, W. Wei, and W. Hu, "Symmetric 40-Gb/s TWDM-PON with 39-dB Power Budget," *IEEE Photon. Technol. Lett.* **25**(7), 644–647 (2013).
3. N. Cheng, X. Yan, N. Chand, and F. Effenberger, "10 Gb/s Upstream Transmission in TWDM PON Using Duobinary and PAM-4 Modulations with Directly Modulated Tunable DBR Laser," presented at the *Asia Communications and Photonics Conference (ACP)*, Nov. 2013, Paper ATH3E.4.
4. Z. Li, L. Yi, W. Wei, M. Bi, H. He, S. Xiao, and W. Hu, "Symmetric 40-Gb/s, 100-km passive reach TWDM-PON with 53-dB loss budget," *J. Lightwave Technol.* **32**(21), 3389–3396 (2014).
5. Y. Guo, S. Zhu, G. Kuang, Y. Yin, Y. Gao, D. Zhang, and L. Liu, "Demonstration of 10G Burst-Mode DML and EDC in Symmetric 40Gbit/s TWDM-PON over 40km Passive Reach," presented at the *Optical Fiber Communication Conference (OFC)*, Mar. 2014, Paper Tu2C.6.
6. D. Qian, E. Mateo, and M. Huang, "A 105km reach fully passive 10G-PON using a novel digital OLT," presented at the *European Conference of Optical Communications (ECOC)*, Sep. 2012, Paper Tu.1.B.2.
7. B. Charbonnier, F. Saliou, B. LeGuyader, and P. Chanclou, "Versatile customers, do we have FTTH solutions," presented at the *European Conference of Optical Communications (ECOC)*, Sep. 2014, Paper Th.2.6.1.
8. Z. Li, L. Yi, and W. Hu, "Comparison of Downstream Transmitters for High Loss Budget of Long-Reach 10G-PON," presented at the *Optical Fiber Communication Conference (OFC)*, Mar. 2014, Paper Tu2C.4.
9. D. Borne, V. Veljanovski, E. Man, U. Gaubatz, C. Zuccaro, C. Paquet, Y. Painchaud, S. L. Jansen, E. Gottwald, G. D. Khoe, and H. Waardt, "Cost-effective 10.7-Gbit/s long-haul transmission using fiber Bragg gratings for in-line dispersion compensation," presented at the *Optical Fiber Communication Conference (OFC)*, Mar. 2007, Paper OThS5.
10. D. van Veen, V. Houtsma, A. Gnauck, and P. Iannone, "40-Gb/s TDM-PON over 42 km with 64-way power split using a binary direct detection receiver," presented at the *European Conference of Optical Communications (ECOC)*, Sep. 2014, Paper PD1.4.
11. 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

Time and wavelength division multiplexed passive optical network (TWDM-PON) has been selected as a primary solution for next generation PON stage-2 (NG-PON2) by ITU-T. With the increasing upstream bandwidth requirement, symmetric 40 Gb/s TWDM becomes an inevitable trend, which requires a 10 Gb/s upstream transmitter. Compared with external modulation schemes, thermally tuned directly-modulated laser (DML) with a small wavelength tuning range is a cost-effective and practical solution for optical network unit (ONU) in TWDM-PON. However 10 Gb/s directly-modulated signals suffer from strong frequency chirp and dispersion induced signal distortion, which can only support around ten kilometers standard single-mode fiber (SSMF) transmission. Therefore dispersion management of upstream 10 Gb/s directly-modulated signals is one of the key factors for the successful implementation of NG-PON2, where at least 40 km reach is required. Various methods have been proposed to solve the dispersion issue to extend the transmission distance and enable long-reach applications with up to 100 km distance. With the wider coverage, the so-called long-reach PON can consolidate the central offices therefore reduce both the operational and capital expenditures of operators. For example, chirp managed laser (CML) could be used to enable more than 100 km transmission [1, 2], but the spectral-reshaping filter after the DML increases the cost a lot, which is not suitable to be used in ONU. Spectral-efficient formats, such as duo-binary and PAM-4 have been used to drive the DML, realizing 20 km fiber transmission but after 40 km transmission the signal quality is severely degraded [3]. We have proposed to use dispersion-supported transmission (DST) effect combining with a delay-interferometer (DI) in optical line terminal (OLT) to mitigate the dispersion effect for all upstream channels, which can achieve similar performances for all the users distributed within 100 km differential reach [4]. But the main issue of this technique is that the central wavelengths of the DI and the DMLs are difficult to be well aligned due to temperature drift, which will affect the practical applications. Apart from the optical solutions, burst-mode electronic dispersion compensation (BM-EDC) at the receiver side in optical line terminal (OLT) can support 40 km transmission with only 1.9 dB penalty compared with the back-to-back (BtB) case [5]. BM-EDC is a potential low cost solution, but its implementation is dependent on the progress of chip design, which is not commercial available at the current stage. So the optical solution is still desired if the commercial available optical components can be used in OLT to manage the dispersion for all upstream channels.

In this paper, by fully making use of the positive chirp of the directly-modulated signals and the characteristics of access networks that lower loss budget is required for the users at shorter transmission distance, we propose to use a single optical dispersion compensator (ODC) operating at ITU-T grid with negative dispersion value in OLT to manage the dispersion for all upstream users with 100 km differential reach. By optimizing the negative dispersion value of the ODC, a maximal loss budget of 51.9 dB for 100 km distance has been achieved, which is even better than the coherent PON case [6]. The loss budget in BtB case is degraded to 38.5 dB, but still with sufficient margin due to low transmission loss. The loss budget is monotonically improved with the increase of the reach, meeting the requirement of access network structure. From the operator's viewpoint, it is also unnecessary to provide same loss budget for the users at the different locations [7]. Experimental results demonstrate that the ODC with fixed negative dispersion value can be used for compensating the dispersion from different transmission distances, which provides a cost-effective and practical solution for the long-reach TWDM-PON.

## 2. System architecture

Figure 1 shows the system architecture of NG-PON2. Based on NG-PON2 standardization, L + band and C- band are used for downstream and upstream wavelengths respectively. For the upstream direction, the DML is modulated by 10 Gb/s pseudo random binary sequence (PRBS) data with a  $2^{31}-1$  word length. The laser wavelength is tuned by temperature with a tuning coefficient of 0.09 nm/°C and the wavelength is stabilized by temperature controller,

which can guarantee less than  $1^{\circ}\text{C}$  temperature variation to avoid wavelength detuning with the arrayed waveguide grating (AWG) used in OLT. The upstream data from all users are combined by a 1: N optical splitter and then transmit through the SSMF. A bidirectional C/L Erbium-doped fiber amplifier (EDFA) is used in OLT to pre-amplify the upstream C-band signal and boost the downstream L-band signal. A C/L coupler is used to separate the upstream and downstream signals. After being divided by a 4-channel AWG with 100 GHz channel spacing, the upstream signals are detected by 4 avalanche photo diodes (APDs) operating at 10 Gb/s. For the downstream direction, since the 4 transmitters are shared by all users, the cost is not very sensitive so CML can be used to support long-reach access [4, 8]. At each ONU, a tunable optical filter (TOF) is required to select the desired downstream wavelength before the receiver.

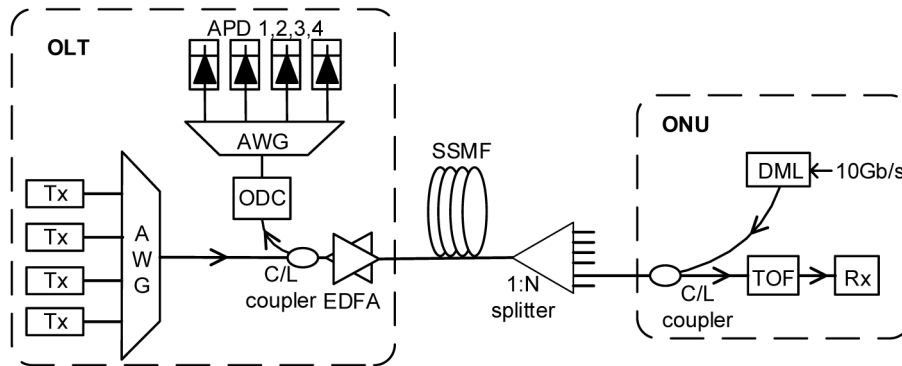


Fig. 1. System architecture of NG-PON2.

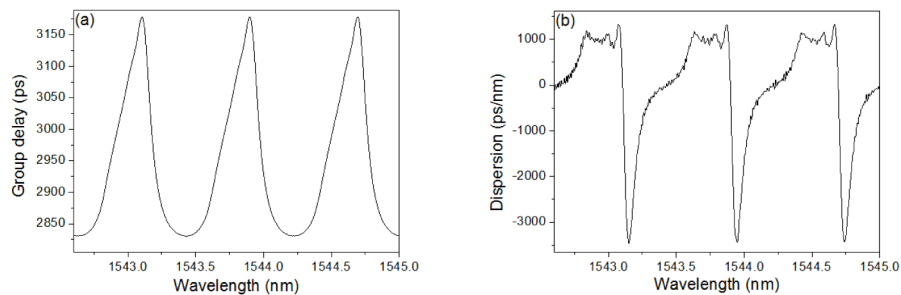


Fig. 2. The measured group delay (a) and calculated dispersion curve (b) of TDC module at dispersion of 1000 ps/nm.

Since the long-reach downstream experiment with high loss budget have been demonstrated in our previous work [4, 8], we only focus on the upstream direction to manage the upstream dispersion using an ODC in this paper. A tunable dispersion compensator (TDC, II-VI network solutions PS3200 consisted of 12 cascaded G-T etalon cavity with 100-GHz channel spacing and mechanical size of  $130 \times 150 \times 15$  mm) with maximal tuning range from  $-2100$  ps/nm to  $+2100$  ps/nm is used to optimize the dispersion value in the experiment, and once the optimal value is defined, an ODC with fixed dispersion value can be used. The measured group delay and calculated dispersion curves of the used TDC module at dispersion of 1000 ps/nm is shown in Fig. 2. Since the derivation of group delay is dispersion, a little unsmooth variation of the group delay will induce great ripple on the dispersion. The 4 dB insertion loss of the TDC module is not an issue for the overall loss budget since it can be fully compensated by the preamplifier. Since the TDC is a multi-channel dispersion compensator with 100 GHz channel spacing, all the four upstream channels in the TWDM-PON can be compensated by a single device. Apart from the etalon-based TDC module, a

chirp fiber Bragg grating (FBG) with negative dispersion value can also be used [9]. Compared with TDC and dispersion compensation fiber (DCF), the FBG is with smaller size and light weight but worse reliability. In the experiment, a C-band EDFA with maximal 35 dB gain and  $\sim 5$  dB noise figure (NF) is used as a preamplifier in OLT. Both the gain and output power are adjustable to achieve the best performance. To support the burst-mode traffic with high dynamic range input power, a burst-mode EDFA is necessary in the practical applications. A TOF with 0.3 nm bandwidth is used to replace the AWG for single wavelength operation. The APD is operated at 10 Gb/s with receiver sensitivity of  $-19$  dBm and saturated power of 1 dBm. The receiver sensitivity for upstream signal is measured before the EDFA in the following experiment.

The directly modulated signal shows a high tolerance to negative dispersion due to its inherent positive chirp, but the signal sensitivity varies with the dispersion values. Considering that the fiber loss for short-distance cases is lower, a degraded performance is acceptable. But the best receiver sensitivity is required for the longest transmission distance. In order to serve all users within 100 km differential reach, the value of the TDC should be optimized. The optimal dispersion value should make the receiver sensitivity monotonically improve with the reach increase and achieve the best value at the longest reach, which is similar as duo-binary signal transmission [10].

### 3. Experimental results and discussions

For demonstrating the feasibility of the method, we firstly set dispersion value at  $-2100$  ps/nm, which is the maximal dispersion value of the used TDC, and the eye diagrams at different distances are shown in Fig. 3, where the DML is operating at 1543.73 nm. The BtB eye diagram is the worst since  $-2100$  ps/nm dispersion is over compensated for the positive chirp of the 10 Gb/s directly-modulated signal. With the increase of the transmission distance, the eye diagram becomes better and achieves the best performance at longest transmission distance, which exactly meets our expectation.

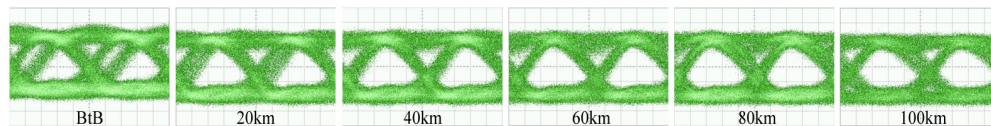


Fig. 3. Eye diagrams of 10-Gb/s upstream signals with different transmission distances for ODC at  $-2100$  ps/nm.

For achieving a high loss budget, we need to optimize the launch power as well as the receiver sensitivity (considering the FEC limit of bit-error-rate at  $3.8 \times 10^{-3}$ ). As we know, the launch power and the chirp value of the DML are determined by the bias current and the driving voltage. We firstly fix the dispersion value at  $-2100$  ps/nm and bias current at 80 mA, corresponding to an output power of 8.3 dBm, then we adjust the driving voltage of DML and measure the receiver sensitivities in different transmission distance cases, as shown in Fig. 4(a). We can see that a higher driving voltage offers a better result at longer transmission distance. This may attributed to higher driving voltage induced larger positive frequency chirp, which is combined with the positive chromatic dispersion of the fiber to fully compensate  $-2100$  ps/nm negative dispersion. The performance at shorter transmission distance is not monotonically varied with the driving voltage, showing the complex chirp characteristic of the laser. Since our target is to optimize the performance at the longest transmission distance, we set the driving voltage at 2 V in the following experiments. Then we investigate the relationship between sensitivity and bias current, the corresponding optical spectra and the measured sensitivities are shown in Fig. 4(b) and 4(c). By operating the DML at different bias currents, the output power and the frequency chirp vary accordingly. For low bias current of 60 mA, the DML output power of 6.2 dBm does not benefit the high loss budget and the BtB sensitivity is also very bad due to too strong frequency chirp. For high

bias current of 100 mA corresponding to 10 dBm output power, the DML is operating at its saturation region and the extinction ratio (ER) is reduced therefore the receiver sensitivity is degraded. The 80 mA bias current corresponding to 8.3 dBm output power results in the best receiver sensitivity. In the following measurement, the bias current and the driving voltage are set at 80 mA and 2 V respectively. Note that 2 V driving voltage and 80 mA driven current are also the nominal operating parameters for a standard DML.

In order to find the optimal dispersion value for the ODC, we need to know the corresponding dispersion value of the chirped directly modulated signal. By varying the dispersion value and measuring the signal sensitivities, we obtain the BtB sensitivity curve as shown in Fig. 4(d). We achieve the best sensitivity when the dispersion value is  $-750$  ps/nm, and the performance is degraded with either higher or lower values. Therefore to achieve the best sensitivity at 100 km distance, it is expected to set the dispersion value at  $-2450$  ps/nm, which can fully compensate the 1700 ps/nm accumulated dispersion after 100 km SSMF transmission and the frequency chirp of the DML.

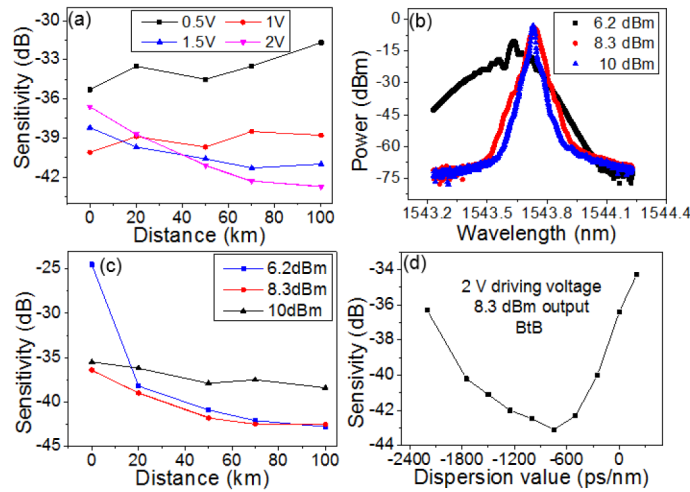


Fig. 4. The sensitivity variation with driving voltage, bias current of the DML and the dispersion value.

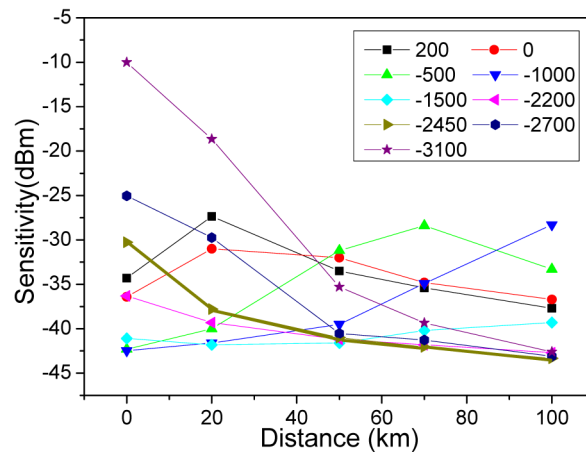


Fig. 5. The sensitivity variation with transmission distance for different dispersion values.

To confirm the optimal dispersion compensation value of the ODC, we cascade a dispersion compensation fiber (DCF) with  $-1000$  ps/nm dispersion value to achieve higher

negative dispersion value and tune the dispersion from 200 ps/nm to  $-3100$  ps/nm to evaluate the sensitivity variation with the transmission distance. The results are shown in Fig. 5. For zero dispersion value, the sensitivity is firstly degraded and then improved with the increase of the transmission distance due to the DST effect [2, 11]. However for practical applications, the receiver sensitivity is required to monotonically improve with the increase of transmission distance and the sensitivity at the longest distance should be the best value. The receiver sensitivity of  $-43.6$  dBm at 100 km distance is the best in the case of  $-2450$  ps/nm dispersion compensation value as we have expected and it is monotonically degraded with the decrease of the transmission distance. In the BtB case, the sensitivity of  $-30.2$  dBm is still acceptable with sufficient margin. The BER curves with different transmission distances at the optimal dispersion value of  $-2450$  nm/ps are shown in Fig. 6. With further increase of the dispersion compensation value, the sensitivity at 100 km reach starts to degrade and the sensitivity at BtB case is degraded significantly. Therefore  $-2450$  nm/ps dispersion is exactly the optimal value for 100 km long-reach access network. Otherwise, if one still desires the same loss budget for different transmission distances as the traditional access networks, dispersion at  $-1500$  ps/nm may be a good value since the sensitivities keep around  $-40$  dBm from BtB to 100 km reach. Note that for the dispersion value varying from  $-1500$  ps/nm to  $-2700$  ps/nm, the degradation of the receiver sensitivity at 100 km reach is less than 3 dB, and the loss budget at BtB case is still with sufficient margin even for the worst case, proving this method has strong tolerance on the frequency chirp of the DML, which is important for practical applications.

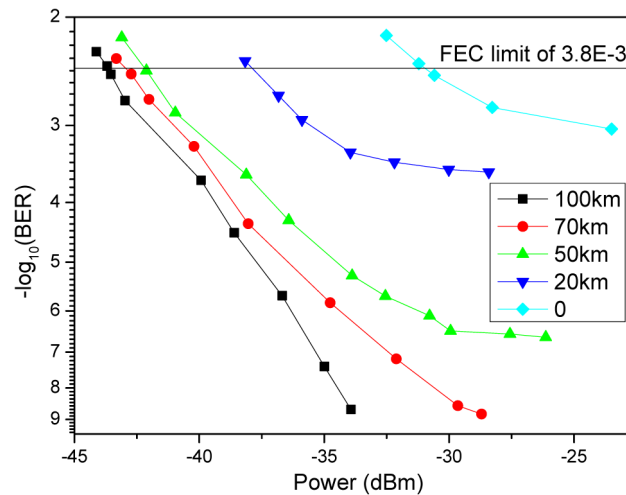


Fig. 6. The BER evolution with different transmission distances at dispersion value of  $-2450$  ps/nm.

**Table 1. Loss budget (LB) evaluation.**

Reach (km)	Tx Power (dBm)	Sensitivity (dBm)	LB (dB)	Fiber loss (dB)	Splitter Loss (dB)	Margin (dB)
0	8.3	$-30.2$	38.5	0	24	14.5
20	8.3	$-37.7$	46	5	24	17
50	8.3	$-41.0$	49.3	12.5	24	12.8
70	8.3	$-42.0$	50.3	17.5	24	8.8
100	8.3	$-43.6$	51.9	25	24	2.9

Finally we evaluate the upstream loss budget of the proposed TWDM PON by fixing the ODC at  $-2450$  ps/nm as shown in Table 1. Since the receiver sensitivity is measured before the preamplifier, the insertion loss of the ODC and the filter will not affect the loss budget

calculation. The loss budget is 38.5 dB for the BtB case and monotonically increased to 51.9 dB for 100 km reach. Here we assume all the users experience the same splitting loss even passing multi-stage splitters. Considering the transmission loss of the SSMF of  $\sim 0.25$  dB/km and the insertion loss of  $\sim 24$  dB for a 1: 128 splitter, the system margin for the BtB case is as high as 14.5 dB and reduced to 2.9 dB for 100 km reach. Therefore it is reasonable to use an ODC with fixed negative dispersion value to support long-reach PON. For the downstream directions, CML based transmitter can support 53 dB loss budget for 100 km differential reach [4] therefore symmetric 40-Gb/s purely passive 100 km TWDM-PON with 51.9 dB loss budget can be realized with stable performance.

#### **4. Conclusions**

In this paper, we demonstrate the feasibility of using a fixed-value ODC at OLT to manage the fiber dispersion with differential transmission distances and the frequency chirp of the 10 Gb/s upstream directly-modulated signal. Considering the characteristics of access networks, it is unnecessary to provide same loss budget for all users with different reaches. We only need to guarantee the best receiver sensitivity for the longest users while keep sufficient margin for the shortest users. By optimizing the dispersion value of ODC, maximal 51.9 dB loss budget can be achieved for 100 km differential reach. More than 1000 ps/nm dispersion tolerance proves the robust of the proposed method, providing a cost-effective and practical solution for long-reach TWDM-PON.

#### **Acknowledgments**

This work was supported National Natural Science Foundation of China (61322507 and 61132004), and Program of Excellent PhD in China (201155).