Simultaneous DPSK demodulation and chirp management using delay interferometer in symmetric 40-Gb/s capability TWDM-PON system

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Abstract: We propose a symmetric 40-Gb/s aggregate rate time and wavelength division multiplexed passive optical network (TWDM-PON) system with the capability of simultaneous downstream differential phase shift keying (DPSK) signal demodulation and upstream signal chirp management based on delay interferometer (DI). With the bi-pass characteristic of DI, we experimentally demonstrate the bidirectional transmission of signals at 10-Gb/s per wavelength, and achieve negligible power penalties after 50-km single mode fiber (SMF). For the uplink transmission with DI, a ~11-dB optical power budget improvement at a bit error ratio of 1e-3 is obtained and the extinction ratio (ER) of signal is also improved from 3.4 dB to 13.75 dB. Owing to this high ER, the upstream burst-mode transmitting is successfully presented in term of time-division multiplexing. Moreover, in our experiment, a ~38-dB power budget is obtained to support 256 users with 50-km SMF transmission.

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

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1. Introduction

Recently, the time and wavelength division multiplexed passive optical network (TWDM-PON) has achieved considerable support from global carriers and vendors in the Full Service Access Networks (FSAN) community [1–3], due to its high data rate and high compatibility with the legacy TDM-PON systems. By stacking 10-Gigabit-capable passive optical network (XG-PON) with multiple pairs of wavelengths onto a deployed optical distributed network (ODN), TWDM-PON combines the benefits of TDM-PON and WDM-PON, and is selected by the ITU-T/FSAN as a primary solution for the next generation PON stage2 (NG-PON2) [3–7]. Using four pairs of wavelength, the TWDM-PON can deliver at least 40-Gb/s downstream and 10-Gb/s upstream aggregate capacity [1, 2]. With the driving of the new services such as big data and wireless backhaul applications etc., the symmetric 40-Gb/s aggregate rate TWDM-PON is considered as a future trend for the NG-PON2 [6].

For simple network deployment and inventory management of TWDM-PON, it is desirable to deploy high-speed colorless tunable transmitter within ONUs. The most common tunable transmitters in WDM-PON system are based on Fabry-Pérot laser diode (FP-LD) or reflective semiconductor optical amplifiers (RSOA). However, FP-LD and RSOA have limited modulation bandwidth (~2GHz). To realize more than 10-Gb/s data rate, electrical or optical equalization is needed but sacrifice the received sensitivities and power budget. Therefore, these tunable transmitters are not the optimal choice for TWDM-PON which requires high system power budget to meet large splitting ratio in optical distribution network (ODN). To address this issue with a cost-effective way, the thermally tuned directly modulated laser diode (DML) has been proposed as a promising solution for the TWDM-PON system [1, 5, 6]. It has the advantages of low cost, compactness, small power consumption, relatively low driving voltage and high optical output power. However, in high-speed DML-based PON systems, the positive frequency chirps significantly limit the maximum achievable system transmission performance [11]. To deal with the chirp of DMLs, we have demonstrated a feasible scheme using a specially-designed tunable optical filter (TOF) installed in the ONU or OLT [5, 6]. However, this specially-designed filter has strict requirements on the profile and bandwidth, which will increase the system cost. On the other hand, the chromatic dispersion in high-speed PON system also limits system performance [12, 13]. Owing to the superior tolerance to the fiber nonlinear and dispersion impairments [14–18], the differential phase shift keying (DPSK) with incoherent detection may be one of

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the promising candidate solution in the TWDM-PON. The 10-Gb/s DPSK downstream transmission has also been widely investigated in the WDM-PON system [19–21]. Therefore, as a relatively mature technique, the DPSK can be employed in the practical implementation of the TWDM-PON system. Meanwhile, since the specific standard of NG-PON2 is not defined yet, it is also worth investigating the DPSK for downstream transmission.

In this paper, for the first time to our knowledge, we propose a symmetric 40-Gb/s capacity TWDM-PON system with a bi-pass DI in ONU to simultaneously realize the downstream DPSK signal demodulation and upstream directly-modulated OOK signal chirp management. In this system, the DI with fixed 10-GHz free spectral range (FSR) is the key component, which plays a two-fold role. It acts as downstream DPSK signals demodulator and is also used as a notch filter to mitigate the dispersion effect caused by the frequency chirp of 10-Gb/s direct modulated upstream signals. This scheme is validated by a symmetric 40-Gb/s TWDM-PON system and the results show that the bidirectional transmissions are free of the power penalties after 50-km single mode fiber (SMF). A ~38 dB optical power budget (OPB) is also achieved to support 256 users in the proposed PON system.

2. Proposed TWDM-PON architecture

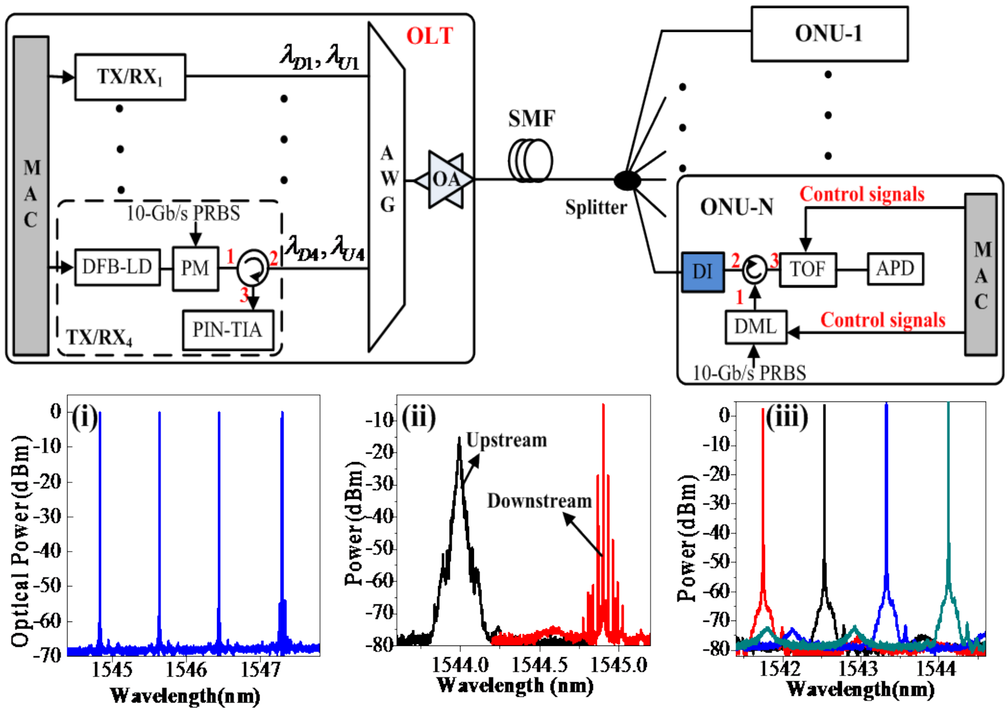

Fig. 1. Architecture of the proposed TWDM-PON system, inset (i) optical spectrum of downstream signals at the output of AWG multiplexer, (ii) optical spectra of upstream OOK and downstream DPSK signals (iii) optical spectra of tuned upstream signals.

Figure 1 illustrates the proposed TWDM-PON system architecture. The OLT has four transmitters and receivers (TXs/RXs) units. In each TX/RX block, the optical carrier is modulated by a phase modulator (PM) to generate DPSK signals. The signals are multiplexed by an arrayed waveguide grating (AWG) and then are amplified by an optical amplifier (OA). The bi-directional OA deployed in the OLT is used to compensate the high optical loss of both upstream and downstream signals. After being transmitted through SMF, the downstream signals are distributed to N ONUs by a 1 × N splitter (N denotes the number of ONUs) in the ODN.

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In ONU, a DI is used to demodulate DPSK signal, and then the signal is fed into a TOF for the downstream wavelength selection before being detected by a receiver (RX). Different from the TOF in our previous report [5], TOF here is only used for the downstream wavelength selection, which relaxes the specific requirements on the TOF [5], therefore reducing the design complexities of ONU. A thermally tuned DML is used as an upstream transmitter. It has a tuning range of 3.0 nm so that each ONU can be tuned to one of the four wavelength channels with 0.8-nm spacing, according to the controlling signals from the media access control (MAC). The DI used for the downstream DPSK signal demodulation plays a second role of suppressing the chirp of upstream signal thus improving the transmission performance. After power coupling and SMF transmission, the upstream signal is firstly pre-amplified by an OA and then detected by a square-law photon detector.

3. Experimental setup and results

Following the configuration of Fig. 1, an experiment is set up for evaluating the performance of this system. At the OLT, four wavelengths at 1544.92 nm, 1545.72 nm, 1546.52 nm and 1547.32 nm, conforming to the ITU-T standard, are selected as the downstream sources. In each TX/RX unit, a LiNbO3 PM is used to generate 10-Gb/s downstream DPSK signal, which is driven by pseudorandom bit sequence (PRBS) data with a length of 231-1. After the AWG, the signals are amplified to 10 dBm per wavelength by a bi-directional erbium-doped fiber amplifier (EDFA). Passing through SMF transmission, the signals are fed into a variable optical attenuator which is used to emulate the loss of the optical splitter and are distributed to each ONU. Before being detected by an avalanche photon-diode (APD), a 10-GHz DI is used to demodulate DPSK signal and then a 100-GHz TOF is employed to select the downstream wavelength channel. Inset (i) of Fig. 1 shows the spectrum of downstream wavelength. The optical spectra of the modulated upstream OOK and downstream DPSK signals are demonstrated in the inset (ii) of Fig. 1.

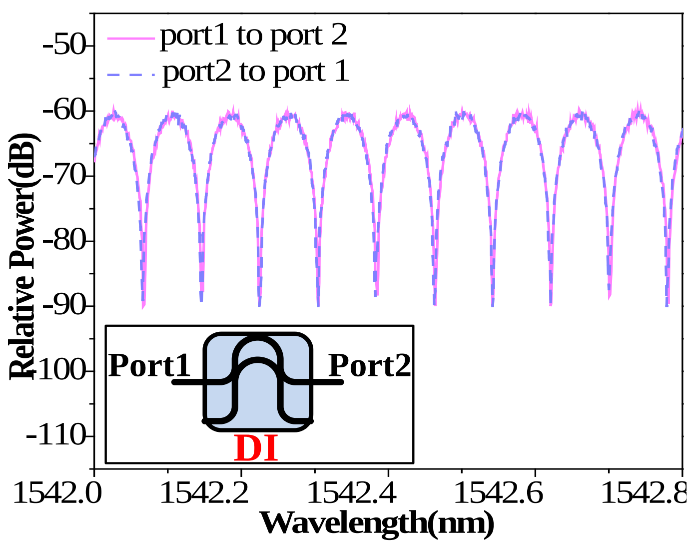

Fig. 2. DI curves for bidirectional transmission, and the inset is the schematic diagram of DI.

For the uplink, we use one 10-Gb/s directly modulated Distributed Feed Back (DFB) laser to emulate different ONUs by adjusting its temperature to tune the output upstream wavelength. During ~60°C tunable range, the output wavelength of DFB varies from 1541 nm to 1544 nm with the stable output power 9 dBm, which can perfectly support 4 upstream wavelengths separated by 0.8 nm as depicted in the inset (iii) of Fig. 1. The DFB biased at 65 mA is driven by the 10-Gb/s PRBS data with the word length of 2^{31}-1. After passing through the splitter and 25-km SMF transmission, the upstream signals are pre-amplified by EDFA

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with an optical gain of ~20 dB. The amplified signals are fed into AWG with 100-GHz channel spacing and then detected by the PIN-TIA for upstream performance measurement.

In order to demonstrate the functions of the DI, we firstly measure the property of the DI. The corresponding bidirectional transmittance curves of DI are depicted in Fig. 2, where the inset is the structure diagram. It is observed that the DI transmittance spectra for the two directions have the same profile, and the corresponding insertion losses for two directions are measured to be 3.96 dB and 3.86 dB respectively. These results indicate that the DI has good bidirectional transmission characteristics. Meanwhile, the transmittance spectrum has better periodicity. Owing to this periodicity, the same type of DI can be installed in each ONU for different wavelength channels processing, which can significantly reduce the inventory cost of TWDM-PON system.

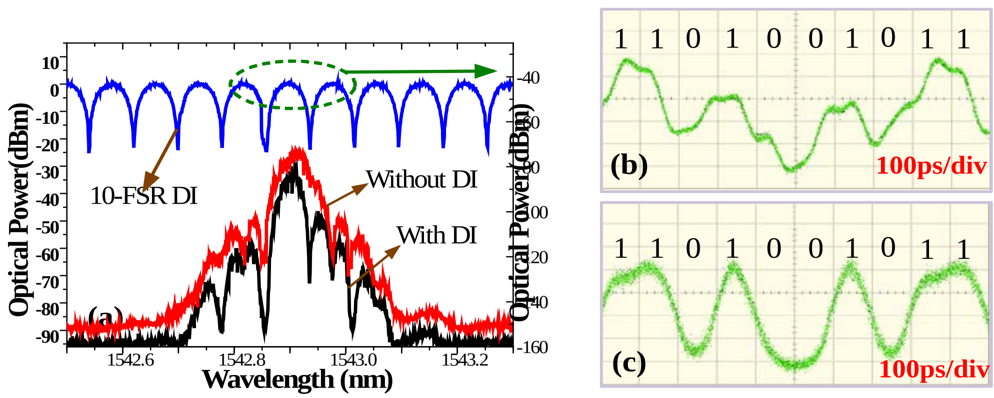

Fig. 3. (a) Optical spectra of the upstream signal without and with DI. The 10 GHz-FSR DI transmittance spectra are also depicted. (b) and (c) are captured waveforms after 50-km SMF transmission without and with DI when the modulation pattern is “1101 0010 11”.

The optical spectra of the upstream signals from the directly modulated DFB laser are shown in Fig. 3(a), which are measured by an optical spectrum analyzer (OSA) with a resolution bandwidth of 0.16 pm. The transmittance curve of 10-GHz FSR DI is also plotted in this picture. The peak wavelength of DI transmittance is detuned 0.02nm to the shorter wavelength from the carriers. Thus, it filters out the red-shift chirp at the leading edges of the signal. In addition, thanks to the periodical filtering of DI, the partial noise floor of DML is also suppressed, therefore improving the signal to noise ratio. In this case, the insertion loss of DI is measured to be ~6 dB. Figures 3(b) and 3(c) show the captured waveforms after 50-km SMF transmission without and with DI, respectively. The applied data pattern is “1101 0010 11”. It is observed that the signal waveform without DI is severely distorted. The reason is that the interaction of the chirp and CD leads to severe inter-symbol interference (ISI) of the transmitting signals. However, with the DI, the signal waveform becomes much better and is nearly the same as the original data pattern, which is shown in Fig. 3(c).

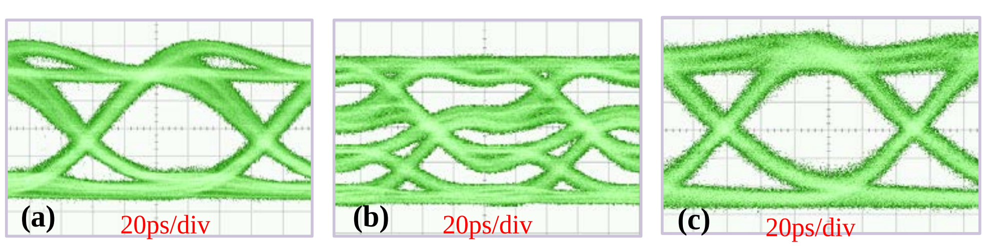

Fig. 4. Eye diagrams for (a) signals without DI in BtB case, (b) signals without DI after 50-km SMF transmission, (c) signals with DI after 50-km SMF transmission.

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Figure 4 demonstrates the measured eye diagrams for the back-to-back (BtB), 50-km SMF transmission without and with DI. For the BtB case without DI, the non-negligible ISI caused by the laser chirp is shown in Fig. 4(a) and the corresponding extinction ratio (ER) is measured to be 3.4 dB. After 50-km SMF transmission, the effect of ISI becomes so serious that the eye is almost completely closed as shown in Fig. 4(b). Using the DI, we observe an obvious performance improvement, as evidenced by a clear and wide open eye in Fig. 4(c). The ER is measured to be ~13.75 dB, which is much higher than the result using the specially-designed TOF in our previous work [5, 6]. The excellent ER improvement is attributed to the preferential attenuations of the "0" s bit frequencies and the DMLs' noise floor with the filtering effect of the DI. The comparisons of upstream signals ER in different chirp management schemes are demonstrated in the Table 1, where the scheme of using the DI achieves the highest ER improvement.

Table 1. Comparisons of the ER and BER performance for the upstream signals with different chirp management schemes for our proposed schemes

chirp management scheme	ER Without filtering	ER with the filtering	Improved ER	Received Sensitivity @1e-9 with 25-km SMF	Received Sensitivity@1e-3 with 25-km SMF
Specially-designed TOF in [4]	3.4 dB	5.6 dB	2.2 dB	~-26 dBm	~-37.7 dBm
Specially-designed TOF in [5]	3.4 dB	7 dB	3.6 dB	~-28 dBm	~-34 dBm
the DI proposed in this paper	3.4 dB	13.75 dB	11.35 dB	~-32 dBm	~-40 dBm

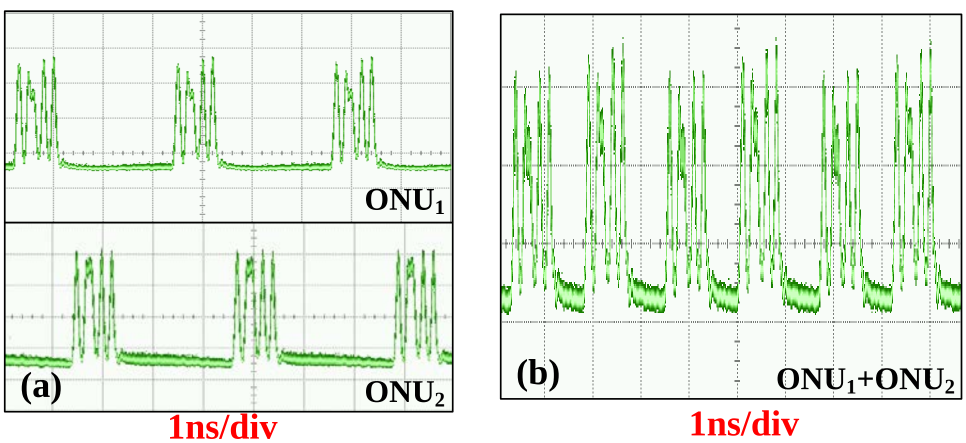

Fig. 5. (a) and (b) are the captured waveforms for ONU_1, ONU_2, and the multiplexed ONU_1 and ONU_2 with burst mode operation.

To prove the feasibility of the proposed upstream scheme in TWDM-PON system, the burst mode operations of upstream transmitter are also experimentally demonstrated. In this experiment, two ONUs operated at the same wavelength and modulated with the 10-Gb/s burst mode signals are coupled together for the proof-of-concept demonstration. Figure 5 shows the waveforms received with the burst mode operation. The ER of t upstream burst mode is measured to be ~13 dB for ONU_1 and ONU_2 as shown in Fig. 5(a). After powering coupling, the combined burst data packets are achieved as depicted in the Fig. 5(b). Owing to this high ER, almost no performance penalty is observed for the ONU_2 in its time slots when the emission power from ONU_1 is not zero, which verifies that our proposed chirp management method is suitable for burst mode transmitting. Note that, the very little power difference between the two burst packets can be attributed to the uneven coupling ratio of the optical coupler used in our experiment.

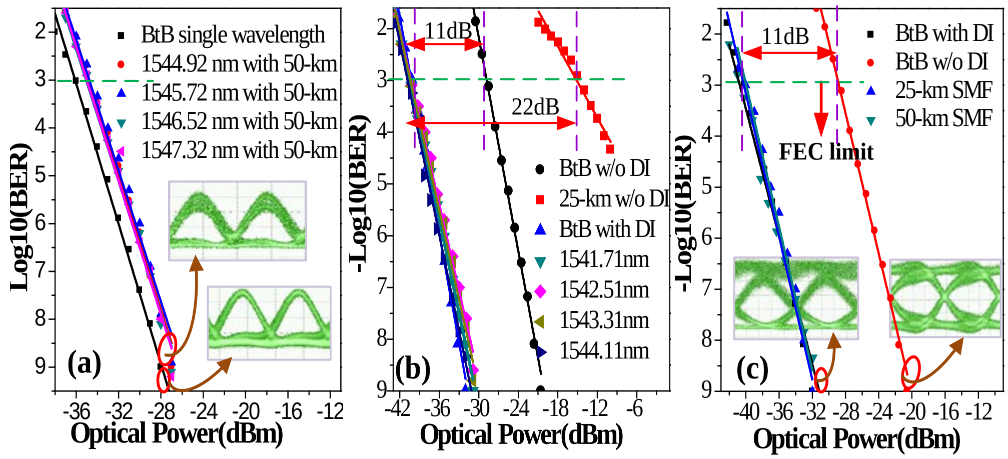

Fig. 6. (a) BERs and eye diagrams for downstream signals over 50-km SMF transmission, (b) BER of upstream signals with DI over 25-km SMF, BtB single wavelength and 25-km SMF without DI (c) BERs and eye diagrams for upstream signals over 25-km and 50-km SMF.

To investigate the transmission performance of the system, we measured BER for upstream and downstream signals as shown in Figs. 6(a)-6(c). These figures show the BtB single-wavelength measurements, as well as the measurements after SMF transmission without dispersion compensation case. In Fig. 6(a), the received power of the worst case for four channels and the BtB case at a forward error correction (FEC) BER limit of 1e-3 is ~-36dBm and ~-35 dBm, respectively. Compared to the BtB case, ~1 dB power penalty is observed for 50-km SMF transmission. Therefore, the CD penalty is negligible for downstream transmission in this system.

The upstream BER performances and eye diagrams for the BtB and 50-km SMF transmission with/without the DI are demonstrated in Fig. 6(c). For the sake of contrastive analysis, the upstream signals with 25-km SMF transmission are also measured, as shown in Fig. 6(b). Compared to the excluding DI case, the ER of upstream signal is improved to 13.75 dB using a 10-GHz FSR DI, resulting in an OPB improvement of 11 dB at a BER of 1e-3. Meanwhile, for the 25-km SMF transmission without DI, we cannot achieve the BER better than 1e-5 even at the maximum received optical power. However, this performance is significantly improved by using the DI. A ~22-dB OPB improvement at the FEC threshold is achieved and almost no power penalty is observed after 25-km SMF transmission. The comparison of upstream signals BER performances between this scheme and our previous reports in [5,6] are also demonstrated in Table1. It is clearly shown that adopting DI to manage chirp can achieve the best BER performance @1e-9 and @1e-3, which can further verify the feasibility of our scheme. Meanwhile, there is no obvious BER performance difference for 25-km and 50-km SMF transmissions. The received sensitivity for 50-km SMF transmission is ~-40 dBm@1e-3.

Finally, according to the sensitivity of the received signal and the output power of the laser source, the maximum supported users of the proposed TWDM-PON architecture are estimated. In the downstream transmission, taking the total loss in the system of 7 dB (including ~3-dB insertion losses of the TOF, ~4-dB insertion loss of the DI) and the sensitivity of the signal of ~-35 dBm into account, the power budget is ~38 dB. As for the upstream link, with the 9-dBm output optical power, and ~6-dB insertion loss of the DI due to the detuning filter of the red-shift chirp signals, we can achieve that the power budget for the upstream link is ~43 dB. Therefore, the power budget of the whole system is ~38 dB, and the

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proposed PON system could support more than 1:256 split ratios. Note that, the power budget of this architecture is limited by the downstream signal, which can be solved by increasing the launched optical power of downstream signals. In that case, the nonlinearities induced by high launched power need to be further investigated.

4. Conclusion

We have demonstrated a symmetric 40-Gb/s aggregate rate TWDM-PON system using the DI for downstream DPSK signal demodulation and upstream directly-modulated OOK signal chirp management. The properties of the DI in bidirectional transmission, the chirp management for upstream signals and the transmission performance of the TWDM-PON system are investigated. The experimental results show that transmittance curves and insertion losses for the bidirectional DI are perfectly consistent. The results also verify that the ER of the upstream signal is improved by 10 dB using the 10-GHz DI, leading to an 11dB OPB improvement at a BER of 1e-3. Furthermore, negligible power penalties are observed in both directions at the 10-Gb/s per wavelength after 50-km SMF transmission. A ~38 dB power budget for this proposed system is also achieved to support more than 1:256 split ratios. Meanwhile, owing to the high ER of the upstream signal, the burst-mode operation is also experimentally demonstrated, further verifying that the proposed scheme could be a promising candidate for the NG-PON2 system.

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