Demonstration of RSOA-Based 20 Gb/s Linear Bus WDM-PON with Simple Optical Add-Drop Node Structure

Han-Hyub Lee, Seung-Hyun Cho, Eun-Gu Lee, and Sang-Soo Lee

We demonstrate a linear bus wavelength-reused gigabit wavelength-division multiplexing passive optical network (WDM-PON) with multiple optical add-drop nodes. A commercially available reflective semiconductor optical amplifier-based WDM-PON has a sufficient power budget to provide multiple optical add/drop nodes in 16 WDM channels. Sixteen 1.25 Gb/s WDM channels are successfully transmitted over 20 km of single-mode fiber with four optical add/drop multiplexers, even with 32 dB reflection and chromatic dispersion in the link.

Keywords: Wavelength-division multiplexing passive optical network (WDM-PON), reflective semiconductor optical amplifier (RSOA), linear bus.

I. Introduction

Looking beyond the currently deployed time-division multiplexing passive optical network (PON) with a 20 km reach and 1:32 split, wavelength-division multiplexing PONs (WDM-PONs) with a higher data rate over 1.25 Gb/s have been developed. WDM-PONs using spectrum-sliced incoherent light sources with WDM multiplexers (MUXs) are very interesting for practical deployment [1], [2]. However, when the spectrum-slicing technique is used, it is often difficult to increase the transmission speed due to the high mode partition noise. One way to reduce this high intensity noise is to use a saturated semiconductor optical amplifier (SOA) or a Fabry-Pérot laser diode after an optical filter, which increases the noise intensity through spectrum slicing [3], [4]. For a WDM-PON configuration, a remodulation scheme, where a downstream optical signal is reused for upstream transmission, has been proposed based on a broadband optical gain medium for optical network terminals (ONTs), such as Fabry-Pérot laser diodes (FP-LDs) [5], [6], semiconductor optical amplifiers (SOAs) [7], or reflective SOAs (RSOAs) [8]. Among the broadband optical gain media, RSOAs have the advantages of high-speed transmission and sufficiently low input power levels [9].

The recently deployed wavelength-reused bidirectional 16-channel WDM-PON with 200 GHz spacing uses RSOAs as colorless optical line terminals (OLTs) and optical network unit (ONU) transmitters [10], [11]. It employs a spectrum-sliced incoherent light as a seed light source, and each spectrally-sliced light is injected into a directly-modulated

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RSOA. Korea Telecom (KT) has deployed a WDM-PON featuring wavelength reuse in a fiber-to-curb network and has successfully provided sixteen 1.25 Gb/s WDM channels. Also, KT has deployed a colorless gigabit WDM/TDM hybrid PON system, which has been successfully supporting commercial triple-play service in a new residential area in Korea since early March 2009 [12].

The wavelength-reuse WDM-PON is bidirectional, and it uses exactly the same wavelength for both downstream and upstream transmissions. One disadvantage is that the link is vulnerable to reflections caused by Rayleigh back scattering, in which the reflected signal induces beat noise against the intended signal at the receiver. To solve this problem, the wavelength-reuse WDM-PON employs a spectrum-sliced method because a spectrally-sliced incoherent light with an Erbium-doped fiber amplifier can act as a reflection-resistible seed light due to its large optical bandwidth.

In the wavelength-reuse WDM-PON, one advantage is that the design of the optical add/drop multiplexer (OADM) can be easily implemented using simple add/drop filters. Commercially available add/drop filters show good performance with a wide operating temperature range of −5°C to +75°C and sufficiently lower insertion loss.

In this work, we investigated a WDM-PON power budget to verify the maximum transmission length and number of add/drop nodes, which are limited because of a chromatic dispersion-induced power penalty and required ONU input power. Also, we experimentally demonstrated a linear bus WDM-PON. By using RSOA transmitters at the OLT and ONU, sixteen 1.25 Gb/s downstream and upstream signals were successfully transmitted over four OADMs spaced at 5 km intervals. Furthermore, the wavelength-reuse WDM-PON with simple OADMs will facilitate the implementation of various topologies of networks such as star, ring bus, and linear bus networks tailored to subscriber needs.

II. WDM-PON Power Budget

A linear bus WDM-PON is easy to implement and extend. However, the length of the fiber and number of nodes is limited by the WDM-PON power budget. To verify the maximum power budget, we measured the bit error rate (BER) characteristics, which include fiber loss and insertion loss of a node, as a function of fiber length and link loss.

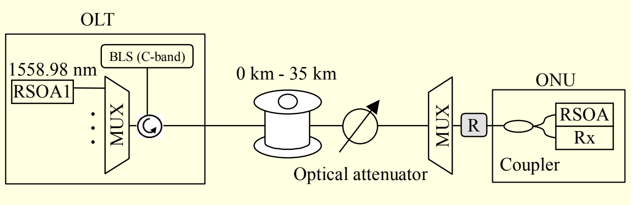


Fig. 1. Experimental setup for measuring WDM-PON power budget.

Figure 1 shows a schematic diagram of the experimental setup. The seed light from a broadband light source (BLS) on the OLT side is spectrum-sliced by a 16-channel MUX which is composed of optical band-pass filters. The channel spacing and optical bandwidth of the MUX are 200 GHz and 140 GHz at 1 dB of transmission bandwidth, respectively. The insertion losses of channels are below 2.7 dB. We measured the BER curve for the channel whose wavelength is 1558.98 nm. The OLT transceiver is a commercially available RSOA-based small form-factor pluggable (SFP) transceiver for generating a downstream signal. The OLT transceiver includes an avalanched photodiode (APD) receiver. The output power was 2 dBm at the front end of the OLT. To generate an upstream signal, an ONU transceiver has a 3 dB power splitter so that the divided downstream signals will input into a PIN photodiode receiver and RSOA simultaneously. All of the OLT and ONU transmitters were directly modulated at 1.25 Gb/s with a non-return-to-zero pseudorandom bit sequence of length 2^7-1. To eliminate the downstream data in the injected signal, the RSOA of the ONU transceiver should operate in the gain saturation regime, which requires high injection power. This imposes an upper limit on the allowable link loss from the OLT to the ONUs. However, after controlling the RSOA gain using a feed-forward current injection (FFCI) technique, we can decrease the required RSOA injection power to −20 dBm [10]. We also had to adjust the decision level of the OLT receiver to improve the upstream signal transmission performance. In this experiment, we adjusted the ONU input power to −15 dBm considering that the ONU transceiver includes a 3 dB power splitter inside. Accordingly, the WDM-PON power budget was limited to 17 dB. To simulate the link reflection, we inserted external reflectors (“R” in Fig. 1) at the front end of the ONU and set the reflection ratio to 32 dB to satisfy the recommendation of [13]. The detailed configuration of the reflector is illustrated in [14]. The WDM-PON employs the spectrally-sliced incoherent light based on the BLS, which has a wider optical bandwidth to minimize optical beating noise between the received signal and the back-reflected signal in the receiver. In a previous work, as expected, we observed no additional power penalty with the external reflector at the front end of both the OLT and ONU [15].

The power budget is limited by a dispersion-induced power penalty resulting from a large optical signal bandwidth. Figure 2 shows the BER curves of downstream and upstream signals as a function of the transmission fiber length. A BER curve of downstream signal shows error floor characteristics for the 35 km transmission; however, we can achieve a

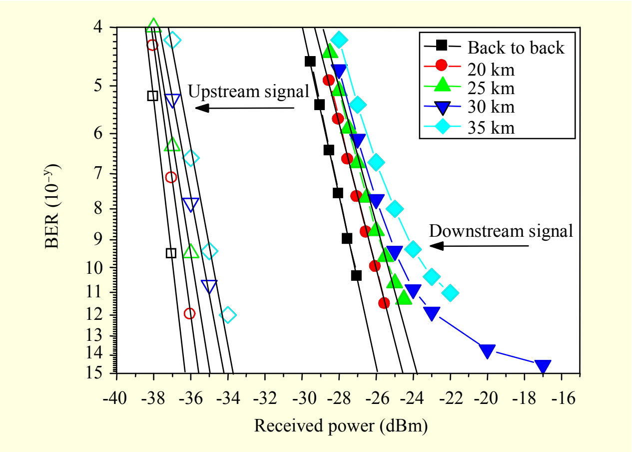


Fig. 2. BER curves as a function of transmission length.

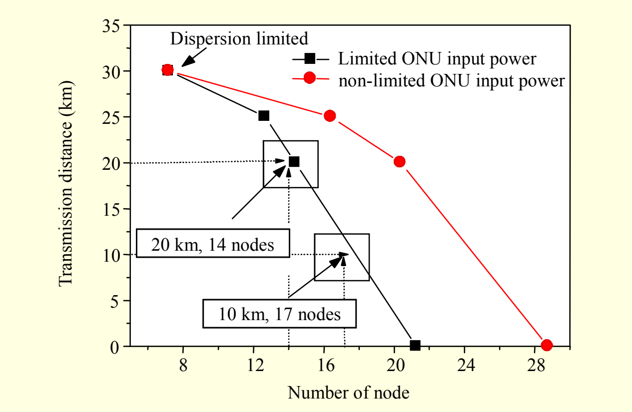


Fig. 3. Transmission distance and number of nodes allowed in a linear bus WDM-PON.

−17 dBm of Rx sensitivity when the BER is under 10^{-14} over a 30 km transmission. In the experiment, we set the extinction ration (ER) of the downstream signal to 6 dB to compromise between transmission performance of downstream and upstream signal in a wavelength reuse technique. Also, the 6 dB downstream ER can satisfy the IEEE standards 802.3 ah. An ER of upstream signal is over 10 dB as shown in Fig. 8(c). No error floor was observed due to relatively high ER of upstream signal over 35 km transmission.

The maximum transmission length is determined by the dispersion-induced power penalty, while the maximum number of optical add-drop nodes is determined by the required ONU RSOA input power rather than Rx sensitivity. Figure 3 shows the transmission distance and number of nodes allowed in the proposed WDM-PON. Here, we consider a node with add/dropping a single channel, and we then set the insertion loss of the node and transmission fiber as 0.8 dB/ea and 0.275 dB/km, respectively. The two limiting regimes of ONU input power and dispersion-induced power penalty are shown in Fig. 3. Curves are shown for two different cases, limited or non-limited ONU input power, at a BER of 10^{-14}. The open squares indicate network candidates in Fig. 3, which have a 20 km reach with 14 nodes and a 10 km reach with 17 nodes.

The transmission limitation from chromatic dispersion is overcome if the BLS in OLT is replaced with a coherent optical source, such as a DFB-LD. However, the transmission performance suffers from optical back-reflection in the link, in which the back reflected signal brings significant beating noise in the Rx. To solve this problem, Lee and others reported that reflection tolerance was improved for a long-reach WDM-PON by operating a DFB LD seed light near its threshold region [16]. By applying a small magnitude of RF signal to a DFB laser near its threshold region, its output spectral bandwidth can be efficiently increased. On the other hand, using coherence detection is a complete solution to reduce the reflection noise from the coherence seed source [17].

III. Linear Bus WDM with Multiple OAMDs over a 20 km Transmission

Figure 4 shows a schematic diagram of the experimental setup. The signal source consists of 16-channels whose wavelengths range from 1535.04 nm to 1558.98 nm with a spacing of 200 GHz. The injected spectrum-sliced seed light to the OLT transmitter is in the range of 0 dBm to 1.7 dBm to effectively suppress intensity noise so that the downstream signal performance is optimized with low jitter variation. The downstream signal is transmitted through a MUX, four OADMs, and four 5 km spans of single-mode fiber. The input power to the ONU transmitter is in the range of −4.3 dBm to −14.3 dBm due to the difference in loss of the transmission fiber and insertion loss of the OADM chain. The dropped downstream signal at each OADM is transmitted to a 50/50 optical coupler in a commercially available ONU transmitter.

1. Optical Add/Drop Multiplexer Characteristics

Figure 5 shows the structure of each OADM. The first and

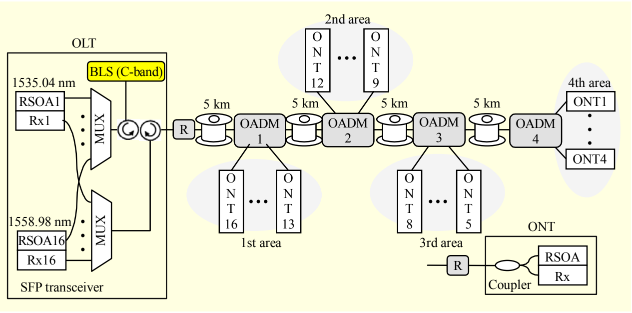


Fig. 4. Schematic diagram of the experimental setup.

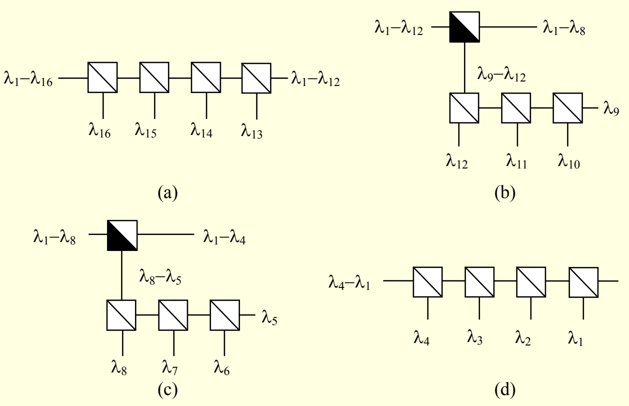
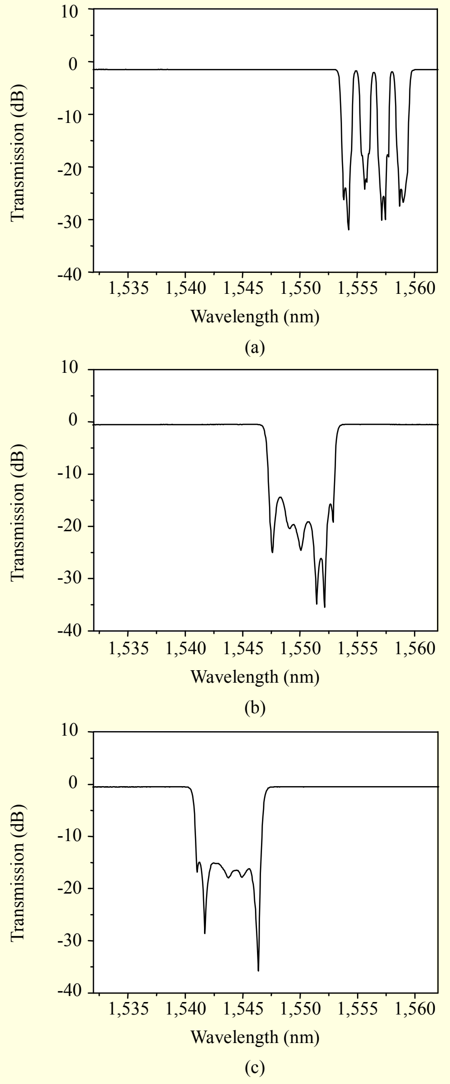


Fig. 5. Configuration of the four optical add/drop nodes: (a) OADM 1, (b) OADM 2, (c) OADM 3, and (d) OADM 4. The symbol ⧅ indicates a 200 GHz band-pass filter, while ⬕ denotes an 800 GHz band-pass filter.

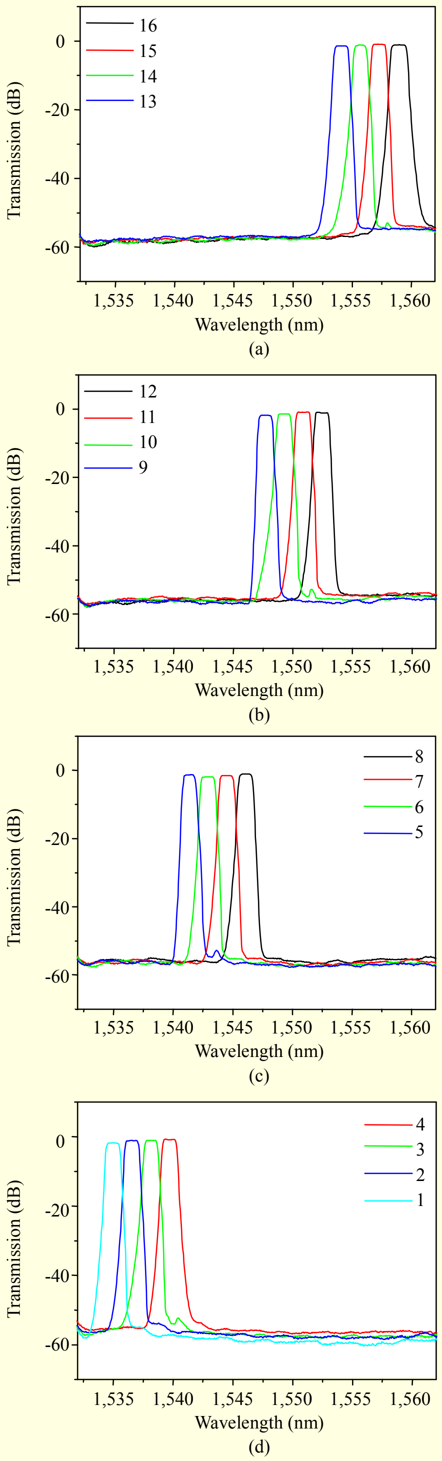


(a)

(b)

(c)

Fig. 6. Transmission spectra of the OADM pass ports: (a) OADM 1, (b) OADM 2, and (c) OADM 3.



(a)

(b)

(c)

(d)

Fig. 7. Transmission spectra of the add/drop ports of each OADM: (a) OADM 1, (b) OADM 2, (c) OADM 3, and (d) OADM 4.

fourth OADMs consist of a cascade of 200 GHz band-pass filters due to the limit of the optical components. The fourth OADM could be replaced with an array waveguide grating. Because the second and third OADMs consist of a cascade of one 800 GHz band-pass filter with three 200 GHz band-pass filters, the insertion loss of the pass ports can be minimized.

Figure 6 shows the transmission spectra for the OADM pass ports. For the reasons mentioned above, the first OADM does not include an 800 GHz band-pass filter, so it exhibits a different transmission characteristic. However, the insertion losses of the pass band as a function of wavelength have a very flat characteristic and 1.5 dB of insertion loss.

Figure 7 shows the transmission spectra for the add/drop ports of each OADM. We expected to see negligible channel-to-channel crosstalk considering that the isolation between neighborhoods is about 40 dB at the center wavelength. Table 1 shows a summary of the insertion loss per channel of the OADMs. The maximum insertion losses of the add/drop and pass ports are less than 1.9 dB and 1.5 dB, respectively.

2. Transmission Results

The optical eye diagrams in Fig. 8 show the downstream and upstream signals with both signals operating simultaneously. The downstream ER was carefully set to 6 dB for generating an upstream signal in a wavelength reuse technique. The downstream eye diagram shows a degraded signal performance after 20 km (see Fig. 8(b)) due to the dispersion-induced intensity noise coming from the 200 GHz channel bandwidth. For the upstream signal, we obtained the clear eye opening shown in the Fig. 8(c), suppressing the one-level thickness by

Table 1. Maximum OADM insertion loss.

Port	OADM 1	OADM 2	OADM 3	OAMD 4
Add/drop	1.5 dB	1.8 dB	1.9 dB	1.9 dB
Pass	1.5 dB	0.5 dB	0.5 dB	None

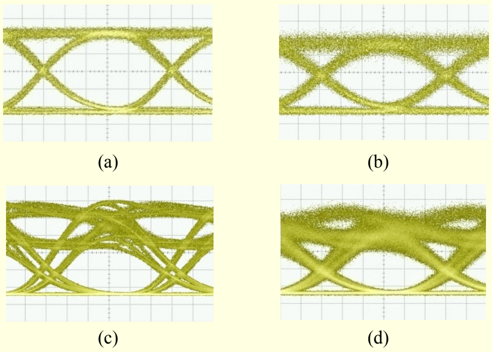


Fig. 8. Eye diagrams for the first channel (1535.04 nm): (a) downstream back-to-back, (b) downstream after transmission of 20 km, (c) upstream back-to-back, and (d) upstream after transmission of 20 km.

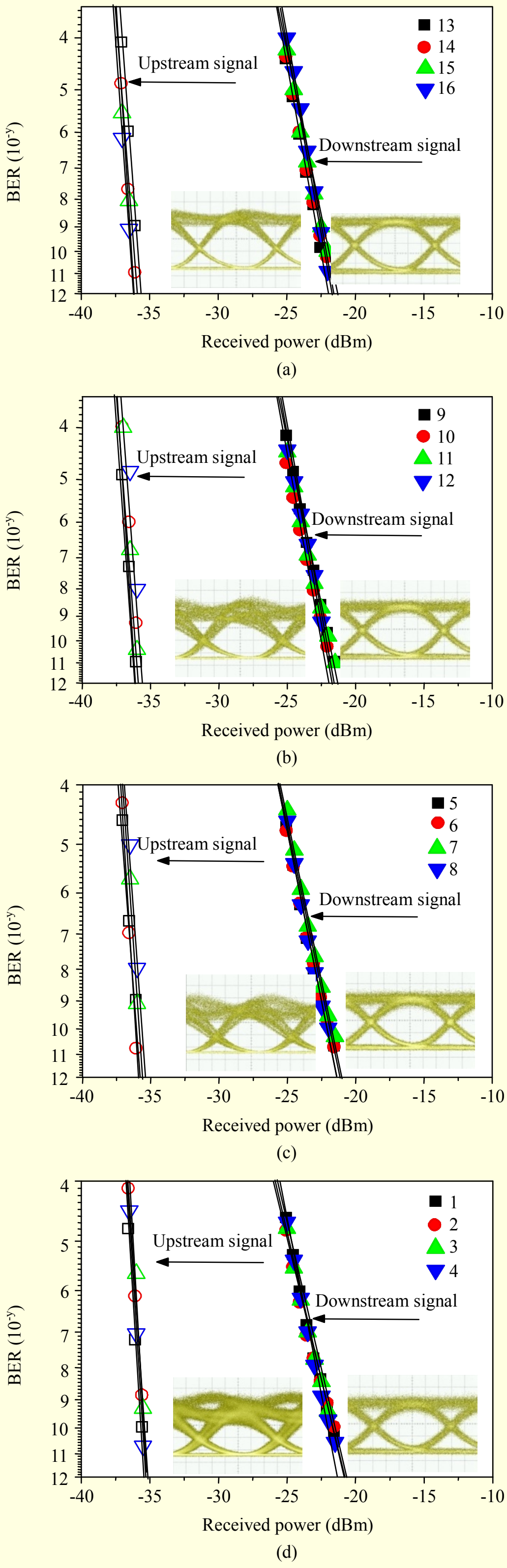


Fig. 9. BER performance of (a) OADM 1, (b) OAMD 2, (c) OADM 3, and (d) OADM 4. The optical eye diagrams indicate the first downstream and upstream channels at each OADM.

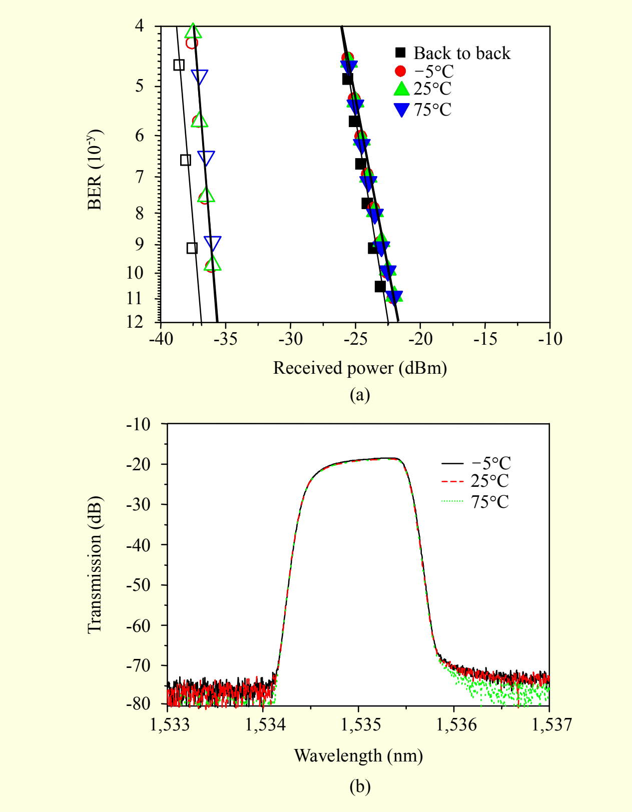


Fig. 10. (a) BER performance and (b) output spectra of a 1535.04 nm channel as a function of operating temperature.

using a gain saturation effect and FFCI function. The upstream eye diagram also shows a degraded signal performance after 20 km (see Fig. 8(d)) due to the dispersion-induced intensity noise.

The solid symbols in Fig. 9 represent the measured BER performance at 1.25 Gb/s for the linear bus WDM-PON in the downstream direction, with the downstream and upstream channels operating through the system simultaneously. The BER curves for different channels were very similar, likely due to the wide gain (entire C-band) of the RSOA for the signal design. We observed the negligible dispersion-induced power penalty after a 20 km transmission. The open symbols in Fig. 9 represent the measured BER performance in the upstream direction. We observed that the downstream data built up linearly on the upstream data level 1, as seen in the insets in Fig. 9, because the power injected into the RSOA in the ONU decreases as it propagates through the OADM chain. However, all of the signals show error-free transmission performance.

To investigate the transmission performance of the OADM under temperature changes, we measured the BER performance of downstream and upstream signals (1535.04 nm) and the output spectrum for OADM 4 versus various temperatures as shown in Fig. 10. The operating temperature range is from −5˚C to 75˚C. No additional power penalty or output spectrum distortion was observed for a temperature variation of 80˚C. This observation was expected since the optical band-pass filter was robust at varying temperatures.

IV. Conclusion

A linear bus WDM-PON uses a commercially available RSOA-based optical transmitter and has a 17 dB power budget to provide multiple optical add/drop nodes in sixteen WDM channels. Sixteen 1.25 Gb/s WDM channels were successfully transmitted over 20 km of single-mode fiber with four optical add/drop multiplexers, even with 32 dB reflection and chromatic dispersion in the link. The four simple OADMs composed of optical band-pass filters, which had low insertion loss and sufficiently wide operating temperatures, can add or drop signals without degradation of transmission performance. The power budget is increased by using a narrower band-pass filter or electrical signal processing to avoid a dispersion power penalty so that the transmission length is extended to over 30 km. Furthermore, considering the simple structure of the OADM, the proposed linear bus WDM-PON is a good candidate for optical access networks for any geographical network topology such as, star, ring, and linear buses.

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