Experimental demonstration of wavelength domain rogue-free ONU based on wavelength-pairing for TDM/WDM optical access networks

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Abstract: In this study, we propose and experimentally demonstrate a wavelength domain rogue-free ONU based on wavelength-pairing of downstream and upstream signals for time/wavelength division-multiplexed optical access networks. The wavelength-pairing tunable filter is aligned to the upstream wavelength channel by aligning it to one of the downstream wavelength channels. Wavelength-pairing is implemented with a compact and cyclic Si-AWG integrated with a Ge-PD. The pairing filter covered four 100 GHz-spaced wavelength channels. The feasibility of the wavelength domain rogue-free operation is investigated by emulating malfunction of the misaligned laser. The wavelength-pairing tunable filter based on the Si-AWG blocks the upstream signal in the non-assigned wavelength channel before data collision with other ONUs.

OCIS codes: (060.4250) Networks; (060.4510) Optical communications.

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1. Introduction

Time division multiplexed (TDM) passive optical networks (PON) are vulnerable to a rogue optical network unit (ONU) in which the ONU transmits burst-mode upstream data in a non-assigned time slot [1,2]. In order to detect and isolate the rogue ONU, several techniques have been proposed, and some methods are described in standard documents [1–4]. Recently, TDM-PON systems have been upgraded to the TDM and wavelength division multiplexed (WDM)-PON in order to accommodate increasing bandwidth demand in the access network [5–10]. TDM/WDM-PONs use several wavelength channels in the system, therefore the ONU in the TDM/WDM system requires to transmit the upstream signal in the assigned wavelength channel as well as time slot. If not, the upstream data in one ONU could collid with upstream data from other ONUs operating at different wavelength channels [7]. This rogue behavior of the wavelength domain can happen due to aging, environmental changes, and user error, during activation or wavelength channel changing of the tunable ONU.

Efforts have been made to mitigate the rogue behavior of the wavelength domain by using a precisely generated wavelength lookup table, an additional wavelength locker in every tunable ONU, and a wavelength demultiplexer in the central office as a centralized wavelength locker [11–16]. These methods, however, increase the cost or complexity of the system. Furthermore, data collision is inevitable when the malfunctioning ONU transmits upstream in the same wavelength channel and time slot, assigned to other ONUs. Thus, it is desirable for the tunable ONU to block the misaligned wavelength output before data collision.

In this paper, a wavelength domain rogue-free ONU based on wavelength-pairing of downstream and upstream signal is proposed and experimentally demonstrated. Since the downstream wavelength is well controlled in the central office, the downstream is utilized as a reference for alignment of the upstream wavelength. The wavelength-pairing filter has a cyclic property, where the free spectral range (FSR) of the filter is designed to transmit the upstream and the downstream wavelength simultaneously. Thus, the misaligned wavelength signals are blocked by the wavelength-pairing filter before data collision with other upstream data. A cyclic Si array waveguide grating (AWG) monolithically integrated with Ge photodiode (PD) is designed and implemented for the wavelength-pairing tunable filter. The wavelength domain rogue-free behavior is demonstrated by measuring the bit error rate (BER) performance of the emulated TDM/WDM optical access network.

2. Principle of wavelength domain rogue-free tunable ONU

Figure 1(a) shows the simplified TDM/WDM optical access network with conventional tunable ONUs. In Figs. 1(b) and 1(c), the normal operation and the potential wavelength domain rogue behavior of one of the ONUs (ONU #2) are illustrated. As shown in Fig. 1(a), downstream data is broadcasted from the optical line terminal (OLT) using several wavelength channels (λ_{D1}, λ_{D2},…λ_{Dk}). These downstream data split to all ONUs in the system. A tunable filter in the ONU selects one of the downstream wavelength channels, and the received optical signal is converted into an electrical signal and then processed by a medium

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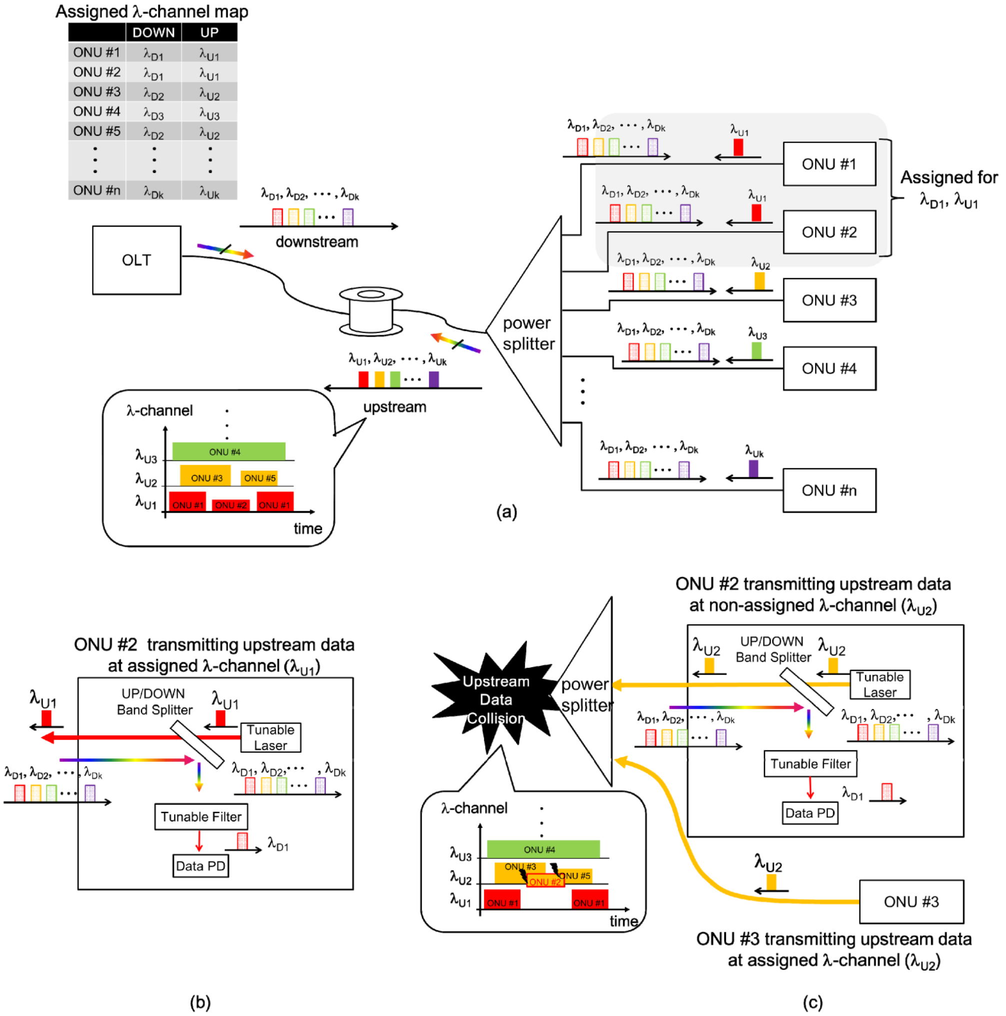
access control (MAC) unit in the ONU. The ONU MAC checks the validity of the downstream signal, and then finds its own pre-defined wavelength channel [17]. After obtaining its wavelength channel map (λ_{D1}, λ_{U1}), ONU #2 transmits the upstream data using its assigned upstream wavelength channel (λ_{U1}). Figure 1(c) shows the rogue behavior when the tunable laser in ONU #2 transmits the output power in the non-assigned wavelength channel (λ_{U2}). The output passes through the upstream/downstream wavelength band splitter. After the power splitter, it is combined with other upstream data at the optical distributed network (ODN), where the data collision happens.



Assigned λ-channel map

	DOWN	UP
ONU #1	λ_{D1}	λ_{U1}
ONU #2	λ_{D1}	λ_{U1}
ONU #3	λ_{D2}	λ_{U2}
ONU #4	λ_{D3}	λ_{U3}
ONU #5	λ_{D2}	λ_{U2}
⋮	⋮	⋮
ONU #n	λ_{Dk}	λ_{Uk}

Fig. 1. (a) Block diagram and wavelength map of the TDM/WDM optical access network, (b) normal operation of the conventional tunable ONU #2 operating at assigned wavelength (λ_{D1}, λ_{U1}) and (c) upstream data collision caused by the rogue behavior of ONU #2 when the tunable laser transmits data at the non-assigned wavelength (λ_{U2}).

Figure 2 shows the proposed wavelength domain rogue-free ONU based on wavelength-pairing of downstream and upstream signal. For wavelength-pairing, it is required to design a wavelength-pairing tunable filter to have a specific FSR. Figure 2(a) shows the assigned wavelength channels in the TDM/WDM system and the transmission characteristic of the filter. The multiple folds of the FSR of the wavelength-pairing tunable filter needs to be the same as a wavelength separation of the downstream wavelength and the upstream wavelength (λ_{Di} - λ_{Ui}) of the system. By aligning the wavelength-pairing tunable filter to one of the downstream wavelength channels, the filter is aligned to the upstream wavelength channel. Therefore, the proposed tunable ONU can transmit the upstream data using the assigned wavelength channel, as shown in the Fig. 2(b). Figure 2(c) shows the situation when there is a malfunction of tunable laser. If the tunable laser transmit the output in the non-assigned wavelength channel (λ_{U2}), the output power is blocked by the wavelength-pairing tunable filter. Thus, there is no upstream output signal from the malfunctioned tunable laser and no upstream data collision. Furthermore, the wavelength rogue-free ONU can monitor its output wavelength as well as block the mis-aligned channel by measuring the transmitted optical power from the wavelength-pairing filter.

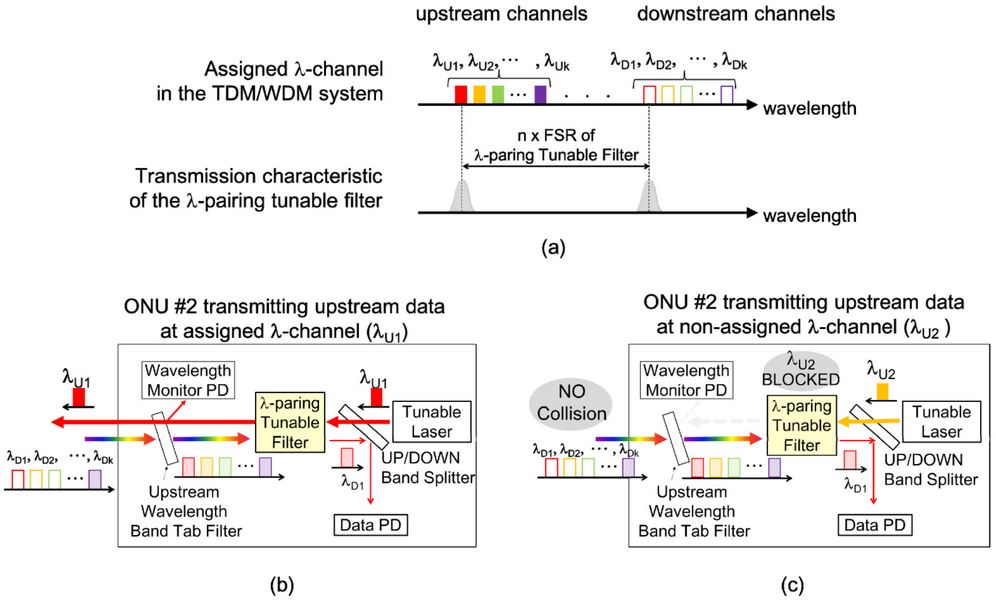


Fig. 2. Proposed rogue-free ONU with up/downstream wavelength-pairing (a) assigned wavelength channels and the transmission characteristic of the wavelength-pairing tunable filter, (b) normal operation of proposed ONU #2 from Fig. 1, operating at assigned wavelength (λ_{D1}, λ_{U1}), and (c) absence of upstream data collision because of the rogue-free nature of ONU #2 when the tunable laser transmits data at the non-assigned wavelength (λ_{U2}).

3. Experimental results and discussions

In order to implement the wavelength-pairing tunable filter for a rogue-free ONU, the cyclic property to have a specific FSR for the target system and FSR-independency when the wavelength-pairing filter is tuned to the other wavelength channels is required. A cyclic Si-AWG was designed and implemented to satisfy these requirements. For size reduction of the ONU, a Ge-PD was integrated with the Si-AWG using silicon photonics technology. Figures 3(a) and 3(b) show the block diagram and the photograph of the fabricated Si-AWG with the Ge-PD, respectively. The designed Si-AWG was fabricated on an 8-inch silicon-on-insulator (SOI) wafer with a 500 nm-thick Si layer and a 2 μm buried oxide. The dimensions of the whole chip were 3 mm x 3 mm even with the integrated PD. The size of the fabricated chip was 100 times smaller than that of a silica AWG. This compact footprint was achieved with the help of the higher refractive index contrast of the silicon waveguide [18,19].

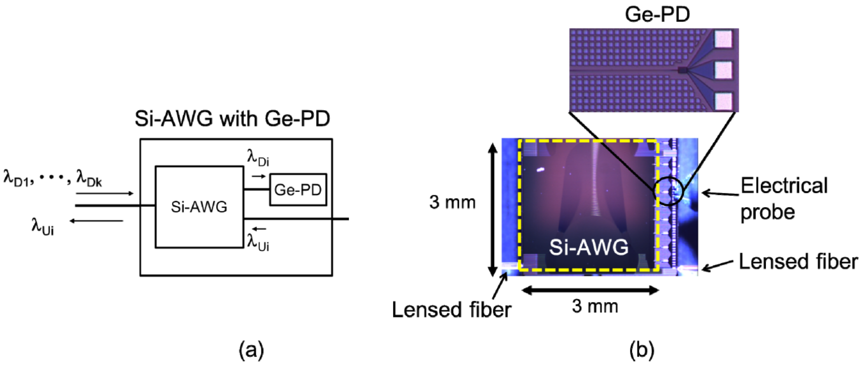


Fig. 3. (a) Block diagram and (b) photograph of the fabricated Si-AWG with Ge-PD

For characterization of the Si-AWG, an optical vector analyzer was used and a lensed fiber was used to couple the Si-AWG. The optical coupling and the propagation loss of the Si-AWG were at 7 dB/facet and 3 dB/mm, respectively. The crosstalk and the channel uniformity were about 18 dB and 3 dB, respectively. The FSR of the cyclic AWG was measured to be 13.8 nm. In order to examine the temperature dependence of the Si-AWG, the Si-AWG was mounted on a thermoelectric cooler (TEC) and temperature of the Si-AWG was changed. Figures 4(a) and 4(b) show the center wavelength of the passband, and the superposition of the transmission spectra at different wavelength bands, respectively. Since we used L-band for the downstream data transmission and C-band for the upstream data transmission the experiments, we measured the passband center wavelength by changing the temperature in C-band and L-band. The measured wavelength shift over a range of temperatures was about 0.9 nm/10 °C. By changing the temperature by 9 °C, the center wavelength of the Si AWG shifted by about 0.8 nm in the C-band and the L-band. Thus, the free spectral range of the passband of the filter is independent of temperature tuning within 27 degree. This means that the Si-AWG can select one of the 100 GHz-spaced downstream wavelength channels. At the same time, the upstream wavelength channel can pass through the Si-AWG simultaneously, which shows that it can function as a wavelength-pairing tunable filter for the rogue-free ONU.

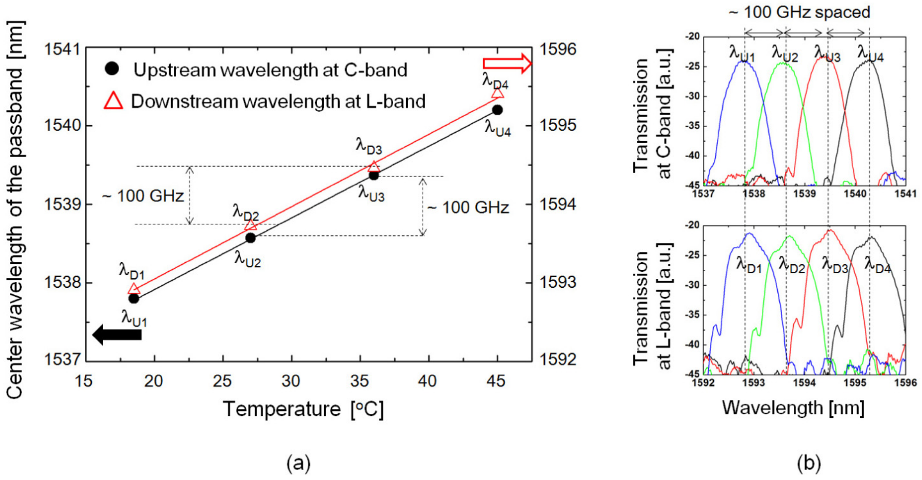
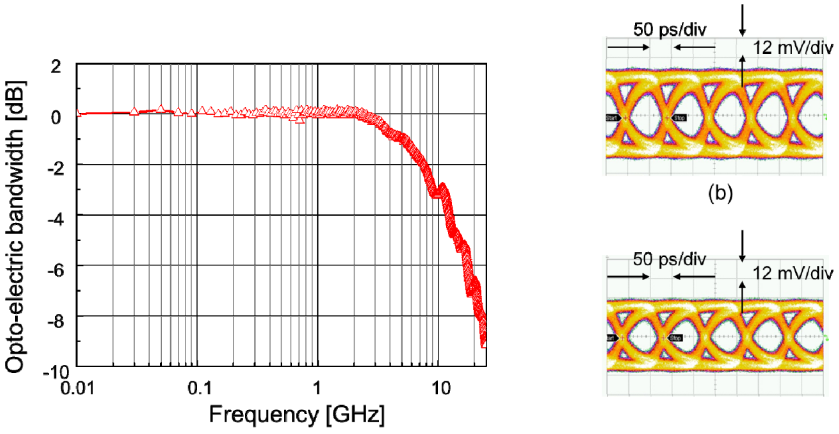


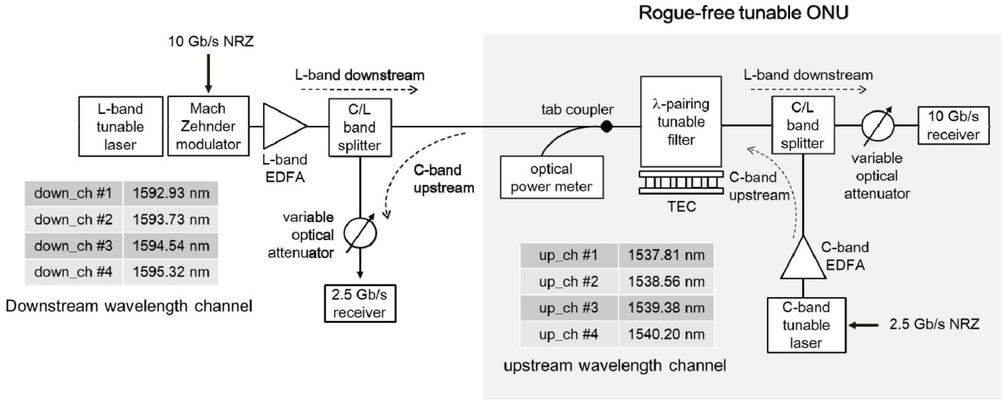
Fig. 4. (a) Temperature dependence of the center wavelength of the passband of the Si-AWG and (b) superposition of the transmission spectra at different temperatures in C- and L-band

Figure 5 shows the measured 3 dB opto-electric bandwidth and the electrical eye-diagram of the Ge-PD integrated with the Si-AWG. An electric probe was used to contact the electrode of the Ge-PD. After inserting 0 dBm through the lensed fiber in the input waveguide of the Si-AWG, the opto-electric bandwidth was meausred using a lightwave component analyzer. As shown in Fig. 5(a), the 3 dB opto-electric bandwidth of the Ge-PD was found to be 9.7 GHz, which guarantees that 10 Gb/s non-return-to-zero (NRZ) data will be received. Figures 5(b) and 5(c) show the electrical eye-diagram of the Ge-PD at temperatures, 18 °C and 27 °C, respectively. The responsivity of the Ge-PD was evaluated using the electrical eye-diagram, and it was measured to be 0.35 A/W. The coupling losses and the propagation losses of the Si-AWG were considered when examining these properties of the Ge-PD.



(a) (c)

Fig. 5. (a) Opto-electric bandwidth and (b) electrical eye-diagram at temperature (b) 18 °C and (c) 27 °C of the Ge-PD integrated with the Si-AWG.



down_ch #1	1592.93 nm
down_ch #2	1593.73 nm
down_ch #3	1594.54 nm
down_ch #4	1595.32 nm

Downstream wavelength channel

up_ch #1	1537.81 nm
up_ch #2	1538.56 nm
up_ch #3	1539.38 nm
up_ch #4	1540.20 nm

upstream wavelength channel

Fig. 6. Experimental setup for BER performance evaluation of the rogue-free tunable ONU

Figure 6 shows the experimental setup for the evaluation of the proposed rogue-free ONU based on wavelength-pairing. The hybrid TDM/WDM optical access network was assumed to accommodate four wavelength channels. The assigned upstream and downstream wavelength channels used in this experiment is shown in the tables in Fig. 6. The L-band was used for the downstream data transmission, whereas the C-band was used for the upstream data transmission. The wavelength separation between downstream and upstream signals was equal to 4 times the FSR of wavelength-pairing filter. For downstream data transmission at OLT, the L-band tunable laser was set to the one of the four 100 GHz-spaced wavelength channels. The output of laser was connected to the Mach-Zehnder (MZ) modulator, which was driven with 10 Gb/s NRZ data from pulse pattern generator (PPG). The pattern length of

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pseudorandom bit sequence (PRBS) was set to be 2^{31}-1 and the output signal of MZ modulator had an extinction ratio of 9.5 dB. The downstream signal was passed through the C/L band splitter used for separating the downstream and the upstream signal. At the ONU side, the downstream signal was connected to a tab coupler, wavelength-pairing tunable filter, and C/L band splitter. Then, it was detected by using a 10 Gb/s receiver instead of Ge-PD for measuring the BER. The passband of wavelength-pairing tunable filter was controlled by temperature to maximize the power of 10 Gb/s receiver. The tunable filter is locked by utilizing the well-aligned downstream from the central office as a reference, and its locking status is maintained by temperature control of the pairing filter. For the upstream data transmission at the ONU, a C-band directly modulated external cavity laser based on polymer Bragg waveguide grating was used [20]. In order to compensate the coupling loss of the Si-AWG, Erbium-doped fiber amplifier (EDFA) is used. The output wavelength was set to one of the upstream wavelength channels. The laser was directly modulated by 2.5 Gb/s NRZ data with PRBS pattern length of 2^{23}-1. The extinction ratio of the modulated upstream output was 7 dB. The modulated upstream signal was coupled to a C/L band splitter and the wavelength-pairing filter and an optical power meter, which was used to monitor the power of the upstream signal. When the upstream wavelength was well aligned to the assigned wavelength, the upstream signal could pass through the pairing filter without blocking. At the OLT side, the upstream signal was connected to the C/L band splitter, and detected by a 2.5 Gb/s receiver.

Figure 7 shows the BER performance of the rogue-free ONU. To investigate the wavelength-pairing function, the wavelength of downstream signal was set to channel #1, which was 1592.93 nm. The center wavelength of the Si-AWG pairing filter was tuned to match this wavelength by changing the temperature (i.e. to 18 °C). The measured sensitivity of downstream signal was −22 dBm at the BER of 10^{-9}, as shown in the Fig. 7(a). In order to evaluate rogue-free operation, three scenarios were investigated. Firstly, the upstream wavelength was set to the wavelength of the upstream wavelength channel #2 (i.e. 1538.56 nm) to emulate malfunction. In this case, the output power measured at the optical power meter was less than −50 dBm, and the upstream BER could not be measured due to synchronization loss. Secondly, the upstream wavelength was set to 1538 nm, which was in the middle of the upstream wavelength channels #1 and #2. It was neither aligned at upstream wavelength channel #1 nor #2. In this case, the monitored power was slightly increased, but the BER was still higher than 10^{-3}. The results of these two cases indicate that the proposed ONU blocks the misaligned wavelength upstream. Finally, we set the wavelength of the C-band laser at upstream wavelength channel #1, which was at 1537.81 nm. By maximizing the optical power, which was measured at the optical power monitor, the C-band laser was aligned within the upstream channel #1. When the upstream wavelength was properly aligned to its assigned wavelength channel, the measured receiver sensitivity was as low as −33 dBm at the BER of 10^{-9}, as show in Fig. 7(b). To check the wavelength channel dependency of the pairing filter, the same scenario was investigated in the down/upstream channels #2, #3, and #4. In this case, we used a single wavelength and tuned its output wavelength to each channel. The results show that the BER was measured only when the upstream wavelength was properly aligned. Furthermore, the misaligned wavelength was blocked, which confirms that the wavelength pairing implemented with the Si-AWG can be used as a rogue-free ONU.

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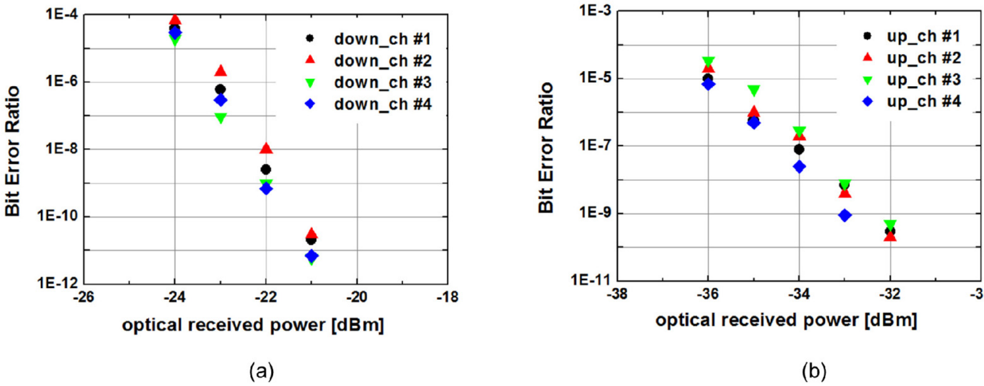

Fig. 7. BER performance of (a) 10 Gb/s downstream at L-band and (b) 2.5 Gb/s upstream at C-band

4. Summary

A wavelength domain rogue-free ONU based on wavelength-pairing of the downstream and upstream signal has been proposed and experimentally demonstrated. Since the wavelength-pairing tunable filter has a cyclic transmission property, the filter aligned to the downstream wavelength channel can transmit the upstream simultaneously, whereas it blocks the misaligned upstream. For implementation of the wavelength-pairing tunable filter, a compact Si-AWG integrated with a Ge-PD was designed and fabricated. The feasibility of the wavelength domain rogue-free operation was confirmed by emulating malfunction of the upstream wavelength. The results show that the wavelength-pairing tunable filter can block misaligned upstream signal before data collision occurs, which could prevent wavelength domain rogue behavior in TDM/WDM hybrid optical access network.

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