Effects of Upstream Incoherent Crosstalk Caused by ASE Noise from Tx-Disabled ONUs in XG-PONs and TWDM-PONs

Han Hyub Lee, Hee Yeal Rhy, Sangsoo Lee, Jong Hyun Lee, and Hwan Seok Chung

A large incoherent crosstalk (IC) caused by amplified spontaneous emission (ASE) noise power from Tx-disabled optical network units and a differential path loss has been shown to degrade upstream transmission performance in time-division multiplexing passive optical networks. This paper considers the IC-induced power penalty of an upstream signal both in an XG-PON and in a TWDM-PON. We investigate the degradation of the extinction ratio and relative intensity noise through a simulation and experiments. For the XG-PON case, we observe a 9.6 dB difference in the level of ASE noise power from Tx-disabled ONUs (hereafter known simply as ASE noise) between our result and the ITU-T XG-PON PMD recommendation. We propose an optical filtering method to mitigate an IC-induced power penalty. In the TWDM-PON case, the IC-induced power penalty is naturally negligible because the ASE noise is filtered by a wavelength multiplexer at the optical line terminal. The results provide design guidelines for the level of ASE noise in both XG-PONs and TWDM-PONs.

Keywords: TWDM-PON, XG-PON, ASE, crosstalk, ONU.

I. Introduction

Next-Generation Passive Optical Network 2 (NG-PON2), based on a 40 Gb/s time- and wavelength-division multiplexed PON (TWDM-PON) and point-to-point (P-t-P) WDM-PON, is under study by the ITU-T Study Group 15 and Full Service Access Network group for the purpose of publishing international standards [1]–[8]. The TWDM-PON has received considerable attention because of its flexibility and scalability, which offer economic benefits in access services. The NG-PON2 has many potential applications in an optical access field and has also been considered for use in wireless back-haul and front-haul [4]–[7]. The physical layered structure of the TWDM-PON is based on tunable WDM technology to allow the flexible operation of an optical access network [2]. The transmission conversion (TC) layer of the TWDM-PON is configured using a 10G-PON (XG-PON) TC layer [3]. In time-division multiplexing passive optical networks (TDM-PONs), such as the XG-PON and TWDM-PON, a burst-mode transmitter (BM-Tx) for an optical network unit (ONU) and a burst-mode receiver (BM-Rx) for an optical line terminal (OLT) require fast Tx enable/disable transient time characteristics [9].

Figure 1(a) illustrates an upstream burst transmission, which consists of a transmitter (Tx) enable transient time, burst transmission, and Tx disable transient time. A directly modulated distributed-feedback laser diode (DFB-LD) is widely used as a 2.5 Gb/s BM-Tx, in which the BM-Tx operates with dc coupling rather than ac coupling, as the dc coupling structure exhibits a better performance with respect to

---

Manuscript received Feb. 3, 2015; revised Sept. 24, 2015; accepted Oct. 7, 2015.

This work was supported by the ICT R&D program of MSIP/IITP, Rep. of Korea (14-000-05-002, Development of key and advanced technologies for high-capacity WDM access networks).

Han Hyub Lee (corresponding author, hanhyub@etri.re.kr), Sangsoo Lee (soolee@etri.re.kr), Jong Hyun Lee (jlee@etri.re.kr), and Hwan Seok Chung (chung@etri.re.kr) are with the Communications & Internet Research Laboratory, ETRI, Daejeon, Rep. of Korea.

Hee Yeal Rhy (heeyeal.rhy@ericsson.com) is with the Strategy Team, Ericsson-LG, Anyang, Rep. of Korea.

http://dx.doi.org/10.4218/etrij.16.0115.0099

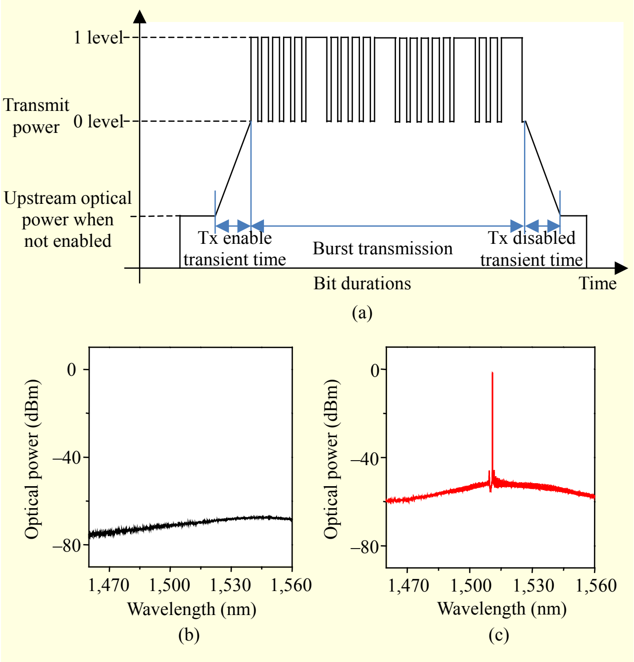


Fig. 1. (a) Burst transmission (in case of 2.5 Gb/s upstream signal in XG-PON; burst length period is 125 μs), (b) BM-Tx output when ONU has no data input, and (c) BM-Tx output when ONU has data input.

Tx transient time.

An ONU BM-Tx should not transmit a signal in bursts that are not assigned to the ONU [2]. In practice, however, the ONU BM-Tx emits an amplified spontaneous emission (ASE) noise continuously, as shown in Fig. 1(b), because the BM-Tx is typically operated under a threshold current by approximately a few milliamperes when the ONU has no data input. The ASE noise power from Tx-disabled ONUs (hereafter known simply as ASE noise) of a commercial G-PON BM-Tx is approximately −45 dBm, as indicated in [10].

Little attention has been paid to incoherent crosstalk (IC) caused by ASE noise in TDM-PONs. The XG-PON and TWDM-PON should support a maximum of 256 ONUs, according to the ITU-T recommendation [1]. And the accumulated ASE noise from 256 ONUs is not negligible, though the ASE noise from a single ONU is negligible. The large IC caused by the ASE noise causes the upstream transmission performance to degrade.

This work considers the IC of the upstream signal, focusing on the IC-induced power penalty caused by the ASE noise. Our goal is to provide appropriate specifications of the upstream optical power of the ONUs when they are not enabled, and mitigation methods to achieve a negligible IC-induced power penalty in both an XG-PON and a TWDM-PON.

Here, in an extension of our previous result [11], we investigate the aforementioned IC-induced power penalty by means of a simulation and experiments. An IC-induced power penalty is predominantly increased by two factors — an accumulated ASE noise from multiple ONUs and 15 dB of differential path loss (DPL) between the ONUs. Hence, we study the IC impairment that arises as a result of these two significant factors. Furthermore, we derive the required specifications for "upstream optical power when not enabled" to ensure a negligible IC-induced power penalty. Further, optical filtering methods are investigated to mitigate IC impairment in both an XG-PON and a TWDM-PON.

II. Numerical Simulation

Figure 2 depicts an XG-PON comprising an OLT, a remote node with a $1 \times N$ power splitter, and multiple ONUs at various distances from the OLT ($d_1, d_2, \ldots, d_n$). We calculate the total ASE noise when 256 ONUs are used in the XG-PON link. The total upstream ASE noise is −21 dBm owing to −45 dBm of the ASE noise of each Tx-disabled ONU. Given that 15 dB of the DPL between the ONUs is allowed in the XG-PONs, the ASE noise from the Tx-disabled ONU can affect the IC impairment significantly [12]. In the worst case, a particular ONU in a Tx-enabled state (for example, ONU-1 in Fig. 2) can experience up to 15 dB of DPL, whereas the remaining ONUs, save for ONU-1, are in a Tx-disabled state; thus, the power of ONU-1 would then be the allowed minimum. The ASE noise accumulates considerably, causing IC in the upstream signal when the signal is received at the OLT BM-Rx.

Considering that the ASE noise is unmodulated, the IC-induced power penalty depends on both the extinction ratio (ER) reduction and intensity noise addition to the wanted signal within a receiver bandwidth, as illustrated in Fig. 3.

From Fig. 3, we can see the ER of the signal is rapidly reduced when "P0" is increased; this is because the ER is defined as the ratio of 1-level power (P1) and 0-level power

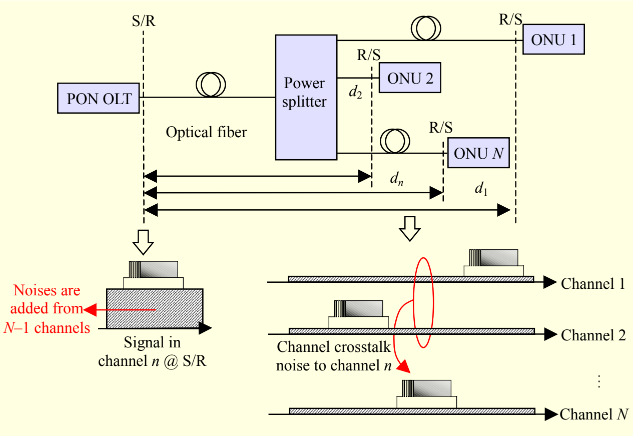


Fig. 2. Impact of IC on system performance in XG-PON.

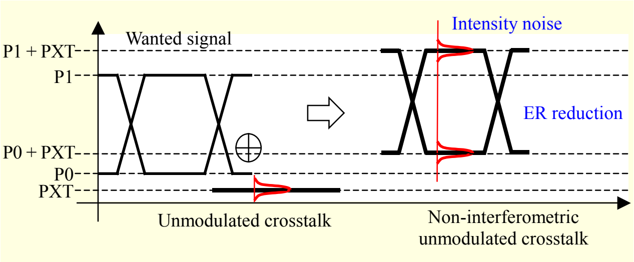


Fig. 3. Non-interferometric unmodulated IC.

(P0) in dB. Therefore, the ER of the signal can be reduced by adding an unmodulated ASE noise (PXT), because “P0” is increased from “P0” to “P0 + PXT.” Moreover, the addition of unmodulated ASE noise into the signal causes degradation of relative intensity noise (RIN); the receiver signal-to-noise ratio is degraded. Consequently, the signal performance is degraded, due to the addition of the unmodulated ASE noise.

The IC penalty (P_c) through a reduction of ER only is calculated using [13]

$$P_{\mathrm{c}} = 10\log\left(\frac{\mathrm{er}'+1}{\mathrm{er}'-1}\right) - 10\log\left(\frac{\mathrm{er}+1}{\mathrm{er}-1}\right) = 10\log\left(1+10^{\frac{\mathrm{XT}}{10}}\right), \quad (1)$$

$$\mathrm{er}' = \left(\frac{2\mathrm{er}}{\mathrm{er}+1}+10^{\frac{\mathrm{XT}}{10}}\right) \Bigg/ \left(\frac{2}{\mathrm{er}+1}+10^{\frac{\mathrm{XT}}{10}}\right), \quad (2)$$

where XT denotes IC (in dB), er is a linear ER without IC effect, and er′ is a degraded linear ER with IC effect (given by (2)). Crosstalk, XT, is a defined ratio of the total power in the ASE noise to that in the wanted channel. Note that the IC penalty (P_c) depends only on the IC (XT) and is independent of the ER of the signal.

If the RIN degradation effect is added to the IC penalty (P_c), then (1) no longer holds; thus, a simulation including a noise addition model and experiment is conducted to obtain the IC penalty functionality. A simulation of the RIN degradation effect caused by ASE noise in the signal was developed through a Gaussian noise addition model (illustrated in Fig. 4). Here, I_1 and I_0 denote the 1-level current and 0-level current of the signal unaffected by the IC, respectively. Further, I'_1, I'_0, I_d, σ_1, and σ_0 are the 1-level current, 0-level current, decision-threshold current, 1-level noise current, and 0-level noise current after the ASE noise is added, respectively.

The “beating” noises from the signal to the ASE noise and from within the ASE noise itself are generally ignored in the simulation because the RIN degradation effect caused by the ASE noise to the signal dominates, considering that the receiver bandwidth is much smaller than the optical bandwidth of the ASE noise. The noise currents are calculated according to [13]

$$\sigma_i^2 = \sigma_{\mathrm{T}}^2 + \sigma_{\mathrm{S}i}^2 + (I_i\gamma_{\mathrm{sig}})^2 + (I_{\mathrm{XT}}\gamma_{\mathrm{XT}})^2 \quad \text{for } i = 0 \text{ or } 1, \quad (3)$$

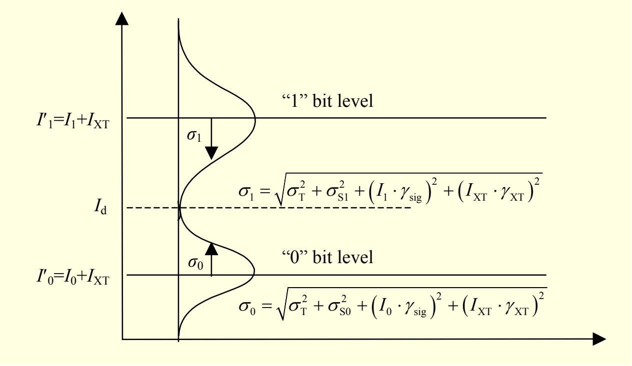


Fig. 4. “1”- and “0”-level signal and noise diagram at receiver.

$$\sigma_{\mathrm{T}}^2 = [4k_{\mathrm{B}}(T+273)R_{\mathrm{L}}]F_{\mathrm{n}}\mathrm{Be}, \quad (4)$$

$$\sigma_{\mathrm{S}i}^2 = 2qM^2F_{\mathrm{A}}I_i\mathrm{Be} \quad \text{for } i = 0 \text{ or } 1, \quad (5)$$

$$\gamma_y = 10^{\frac{\mathrm{RIN}\times y}{10}}\mathrm{Be} \quad \text{for } y = \mathrm{sig} \text{ or XT}. \quad (6)$$

In the above equations, σ_{T}, σ_{S1}, σ_{S0}, γ_{sig}, and γ_{XT} are the thermal noise, 1-level shot noise, 0-level shot noise, RIN noise ratio of the signal, and RIN noise ratio of the crosstalk, respectively. In addition, k_{B}, T, R_{L}, F_{n}, Be, q, M, and F_{A} are the Boltzmann constant, temperature in degrees Celsius, load resistance, noise-enhancement factor, receiver bandwidth, electron charge, avalanched photodiode (APD) amplification factor, and excess noise factor of the APD, respectively.

In our simulation, we used an APD receiver rather than a p-i-n PD receiver to investigate worst-case XG-PON design. RIN is measured in the unit of dBc/Hz, whereas the RIN noise ratio is dimensionless. In the simulation using (3) through (6), T = 25 °C, R_{L} = 2.7 kΩ, F_{n} = 2, Be = 1.8 GHz for a 2.5 Gbit/s operation, M = 10, and F_{A} = 7.6 are used. The RIN value of the Tx source is –120 dBc/Hz, which is used and is the minimum RIN value to ensure a 2.5 Gb/s transmission. In addition, the RIN of the DC noise is –110 dBc/Hz. When the signal and the ASE noise are received at the receiver, the bit error rate (BER) of the signal is calculated using [14]

$$\mathrm{BER} = \frac{1}{4}\left[\mathrm{erfc}\left(\frac{I'_1-I_{\mathrm{d}}}{\sigma_1}\right)+\mathrm{erfc}\left(\frac{I_{\mathrm{d}}-I'_0}{\sigma_0}\right)\right], \quad (7)$$

where erfc(x) stands for the complementary error function, defined as [15]

$$\mathrm{erfc}(x) = \frac{2}{\sqrt{\pi}}\int_x^{\infty}\exp(-y^2)\,\mathrm{d}y. \quad (8)$$

III. Experiments

Figure 5 shows the experimental setup for the unmodulated

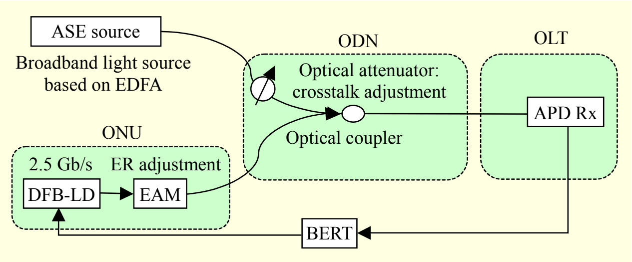


Fig. 5. Experiment setup.

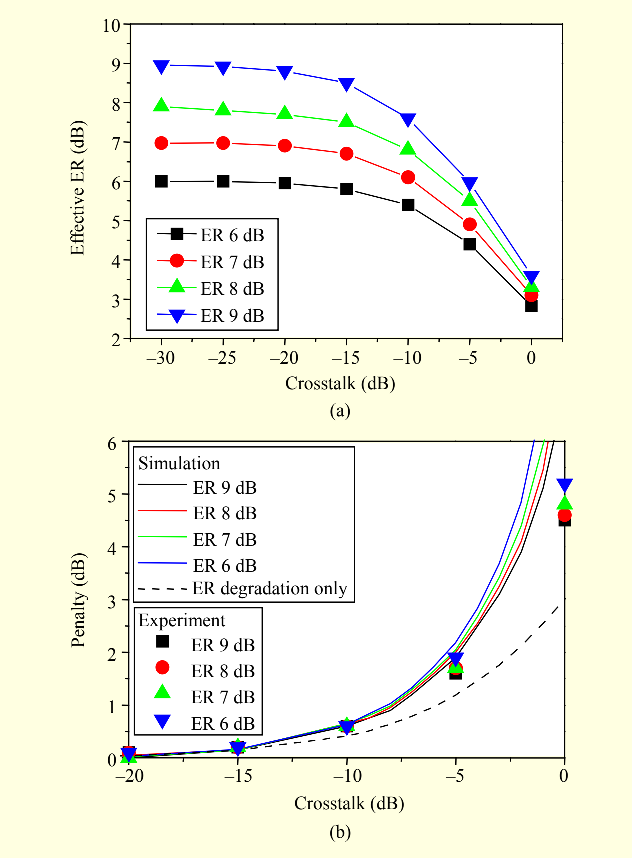


Fig. 6. (a) ER reduction as function of IC and (b) measured and simulated penalties as function of IC.

IC impairment study. A signal is modulated at 2.488 Gb/s (a pseudorandom bit sequence of length 2^{31}–1, non-return-to-zero) by an external modulator. The power level of the ASE noise from the ASE source is adjusted using an optical attenuator to vary the IC level. The IC is calculated as the power difference ratio between the signal power and the ASE noise from the ASE source in front of the Rx. An APD receiver is used to measure the IC-induced power penalty.

Figure 6(a) shows a comparison indicating the effective ER reduction of the signal. We vary the ER of the 2.5 Gb/s signal from 6 dB to 9 dB. In the low-IC regime of <–15 dB, the ER is changed slowly. However, the ER changes considerably in the regime where the IC is larger than –15 dB. Note that the ER of the IC-affected signal converges at 3 dB — a result that is independent of the ER of the unaffected signal as the IC approaches 0 dB, which is explained through (1).

The IC-induced power penalty is also measured as a function of the IC, as shown in Fig. 6(b). Further, it is calculated through the simulation, considering both the ER reduction and the RIN degradation of the 2.5 Gb/s signal caused by the ASE noise. The measured penalty data (dots), the calculated penalty curve (dashed line) according to (1), and the simulated penalty curves (solid lines) are provided. The simulation results for both the ER reduction and the RIN degradation agree well with the measured data. These results suggest that the IC must be below −20 dB to ensure a negligible IC-induced power penalty.

1. Upstream Optical Power When ONU is Not Enabled in XG-PON

We calculated the IC for the XG-PON case using the following equations. The units are dB or dBm.

$$P_{\mathrm{Rx}} = P_{\mathrm{ONU}}^{\mathrm{Min}} - d_{\mathrm{Max}} - L_{\mathrm{splitter}}, \tag{9}$$

$$P_{\mathrm{Noise}}^{\mathrm{Max}} = P_{\mathrm{ONU}}^{\mathrm{Off}} + 10\log(N-1) - L_{\mathrm{splitter}}, \tag{10}$$

$$\mathrm{XT} = P_{\mathrm{Rx}} - P_{\mathrm{Noise}}^{\mathrm{Max}} = P_{\mathrm{ONU}}^{\mathrm{Off}} + 10\log(N-1) - P_{\mathrm{ONU}}^{\mathrm{Min}} + d_{\mathrm{Max}}, \tag{11}$$

$$P_{\mathrm{ONU}}^{\mathrm{Off}} = \mathrm{XT} - 10\log(N-1) + P_{\mathrm{ONU}}^{\mathrm{Min}} - d_{\mathrm{Max}}. \tag{12}$$

Here, P_{Rx} and $P_{\mathrm{ONU}}^{\mathrm{Off}}$ are the minimum sensitivity at the BER reference level and minimum output power of the ONU Tx, respectively. In addition, d_{Max} is the maximum DPL, L_{splitter} accounts for the insertion loss of the optical splitter, N is the number of ONUs, XT is the IC, and $P_{\mathrm{ONU}}^{\mathrm{Off}}$ is the upstream optical power when the ONU is not enabled. The maximum value of d_{Max} is limited by the following equation:

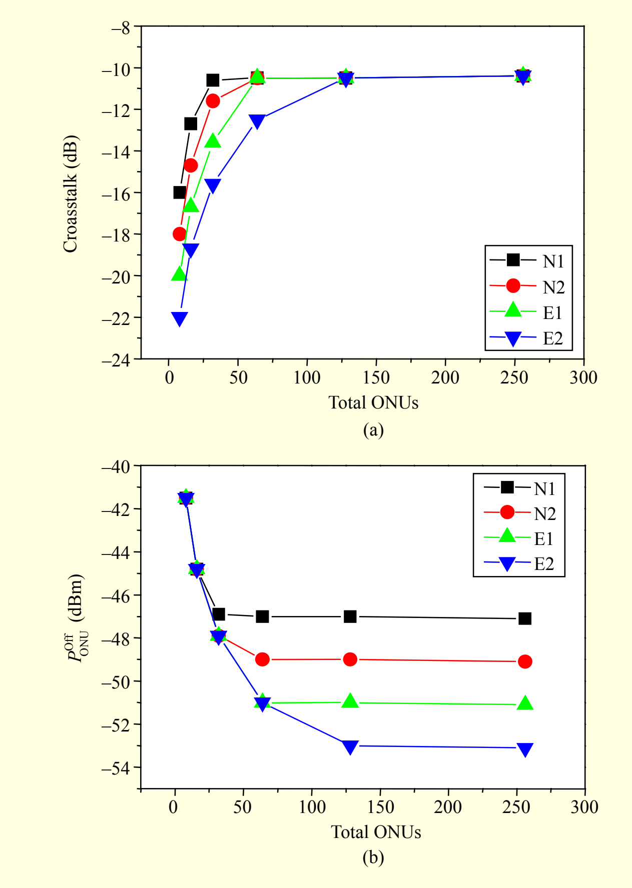
$$d_{\mathrm{Max}} \le \mathrm{LinkBudget}_{\mathrm{PON}} - L_{\mathrm{splitter}}. \tag{13}$$

The splitter loss (L_{splitter}) is calculated assuming a 3 dB loss for each 1 : 2 split, considering the worst-case system design approach. For the values of $P_{\mathrm{ONU}}^{\mathrm{Off}}$, we referred to the values given in the ITU-T G987.2 recommendation; $P_{\mathrm{ONU}}^{\mathrm{Off}}$ is defined in such a way so as to be 10 dB lower than P_{Rx}. The recommendation also provides optical distribution network (ODN) classes in four different optical-path losses, such as nominal1 (N1), nominal2 (N2), extended1 (E1), and extended2 (E2). Typically, N1 class is widely used for real deployment. Table 1 summarizes the budget, P_{Rx}, and $P_{\mathrm{ONU}}^{\mathrm{Off}}$ of each ODN class.

The ITU-T G987.2 standard recommends a maximum 1 dB of chromatic-induced power penalty for C-band upstream

Table 1. $P_{\mathrm{ONU}}^{\mathrm{Off}}$ in XG-PON [16].

Link class	N1	N2	E1	E2
Budget	29 dB	31 dB	33 dB	35 dB
P_{Rx}	–27.5 dBm	–29.5 dBm	–31.5 dBm	–33.5 dBm
$P_{\mathrm{ONU}}^{\mathrm{Off}}$	–37.5 dBm	–39.5 dBm	–41.5 dBm	–43.5 dBm



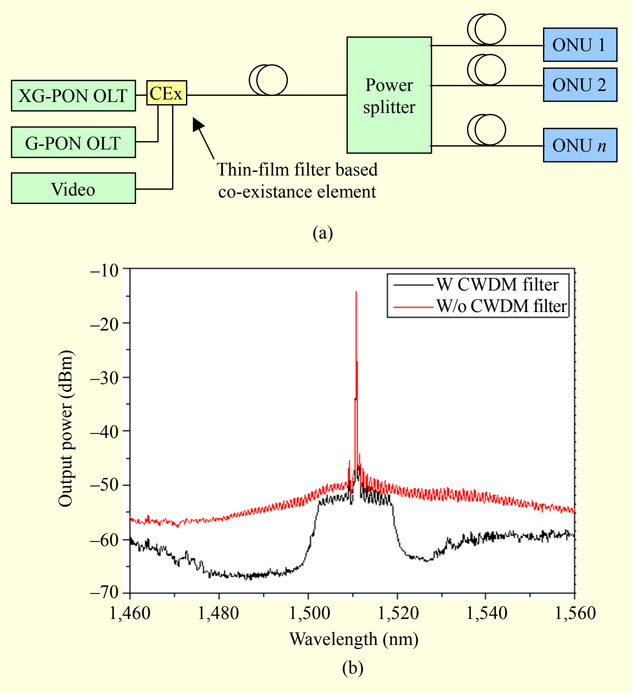
(a)

(b)

Fig. 7. (a) Crosstalk as function of all ONUs and (b) $P_{\mathrm{ONU}}^{\mathrm{Off}}$ as function of all ONUs having –20 dB of IC.

signal transmission. The aforementioned chromatic-induced power penalty is an important parameter in the design of optical links. However, in the ITU-T G.987.2 standard, no consideration is given to an optical IC-induced power penalty. It means that the IC-induced power penalty should be negligible for an upstream signal transmission.

In Fig. 7(a), the IC increases with the total number of ONUs but is fixed to −10.4 dB for all of the link budget classes when the PON has more than 128 ONUs. This is because of the d_{Max} condition described in (13). The crosstalk of −10.4 dB corresponds to a 0.7 dB IC-induced power penalty, as shown in Fig. 6(b). This means that the value of $P_{\mathrm{ONU}}^{\mathrm{Off}}$ recommended by the current standard is insufficient for the IC-induced power penalty to be free from IC. To overcome this problem, we calculate a sufficient value of $P_{\mathrm{ONU}}^{\mathrm{Off}}$. Figure 7(b) shows the calculated $P_{\mathrm{ONU}}^{\mathrm{Off}}$ value as a function of the total number of ONUs when the IC is set to −20 dB. For the E2 class, including 256 ONUs, as the worst case, the $P_{\mathrm{ONU}}^{\mathrm{Off}}$ should be less than −53.1 dBm for the IC to be less than −20 dB. There is a 9.6 dB difference between the $P_{\mathrm{ONU}}^{\mathrm{Off}}$ and recommended $P_{\mathrm{ONU}}^{\mathrm{Off}}$ of −43.5 dBm for the E2 class, according to ITU-T G.987.2 [17].



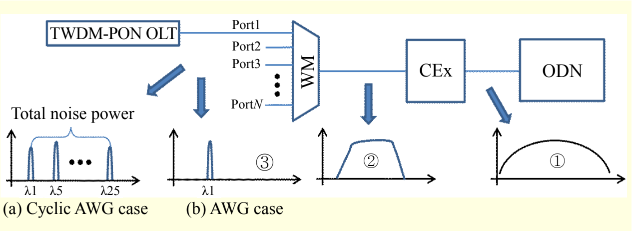
(a)

(b)

Fig. 8. (a) Co-existence of PON services using CEx and (b) ASE noise reduction using CWDM filter.

To compensate for the power difference, we propose the use of an optical bandpass filter (OBPF) located in front of the XG-PON OLT. A good candidate for the OBPF is a co-existence element (CEx) with the purpose of co-existence with legacy services. The usage of a CEx is defined in ITU-T G.987.5, as shown in Fig. 8(a) [16]. The CEx is configured with cascaded thin-film filters and thus the bandwidth of the OBPF can be easily adjusted to fit the XG-PON upstream band. Figure 8(b) shows the optical spectra of the signals with and without the OBPF.

The ASE noise from the DFB-LD with an optical noise bandwidth of over 100 nm is filtered using a coarse WDM (CWDM) filter. An ASE noise from the DFB-LD reduction of 8 dB is achieved using the CWDM filter. This reduction compensates for the gap between the value of the current standard and our calculation result. This suggests that the addition of the CEx filter designed for the upstream band of the XG-PON is a superior method to replacing deployed ONUs



(a) Cyclic AWG case (b) AWG case

Fig. 9. ASE noise filtering using CEx and WM using (a) cyclic AWG and (b) normal AWG.

for improving system performance.

2. Upstream Optical Power When ONU is Not Enabled in TWDM-PON

Because the TWDM-PON is a multiple-wavelength PON system, the TWDM-PON OLT uses the wavelength mux (WM). An arrayed waveguide grating (AWG) or a thin-film filter device is applicable to the WM. Figure 9 illustrates the ASE noise spectra after the WM, a CEx, and the ODN.

The broadband ASE noise spectrum became narrow through optical filtering using the CEx and WM, as shown in Fig. 10(a). We measured the IC-induced power penalty improvement of the 2.5 Gb/s upstream signal when a 100 GHz channel-spacing AWG was used as the WM, as shown in Fig. 10(b).

According to the ASE noise reduction, the IC was enhanced by 20 dB compared with the case without the AWG. Consequently, given the IC reduction, we proposed that the $P_{\mathrm{ONU}}^{\mathrm{Off}}$ of the TWDM-PON ONU should be –33.1 dBm. A wavelength-set division multiplexing (WSDM) scheme was recently developed by Bell Labs as the preferred solution for cost reasons [18]. In this scheme, an ONU uses a DFB-LD-based Tx without a wavelength selection and with an on-chip heater for the wavelength tuning. An OLT uses a cyclic AWG [19]. In contrast to the case with a typical AWG, the total ASE noise at each output port of the WM increased owing to the transmission characteristics of the cyclic AWG. For example, for a 4-channel TWDM-PON system, the cyclic AWG has a 400 GHz free spectral range, as shown in Fig. 9(a).

Therefore, the filtered ASE noise is output periodically at each AWG output port. Because the upstream wavelength band of the TWDM-PON ranges from 1,524 nm to 1,544 nm, 8 × filtered ASE noise with 400 GHz channel-spacing is transmitted at each output port of the cyclic AWG. The filtered ASE noise at each AWG port is not the same, due to the wavelength dependence in the ASE power difference. We normalized all filtered ASE noise to the maximum value of the $P_{\mathrm{ONU}}^{\mathrm{Off}}$ of the TWDM-PON ONU to simplify the analysis and analyze the worst-case IC. Consequently, the total ASE noise is 8.4 dB larger than that of the non-cyclic AWG case. Accordingly, the $P_{\mathrm{ONU}}^{\mathrm{Off}}$ of the TWDM-PON ONU is decreased to –41.5 dBm. In the ITU-T G.989.2, the minimum channel spacing for the upstream signal is defined as 50 GHz. The cyclic AWG will have a 200 GHz free spectral range when the number of channels and the channel spacing are four and 50 GHz, respectively. Therefore, 16 × filtered ASE noise with 200 GHz spacing is transmitted at each output port of the cyclic AWG. The $P_{\mathrm{ONU}}^{\mathrm{Off}}$ of the TWDM-PON ONU is –44.5 dBm for a 50 GHz channel-spacing case.

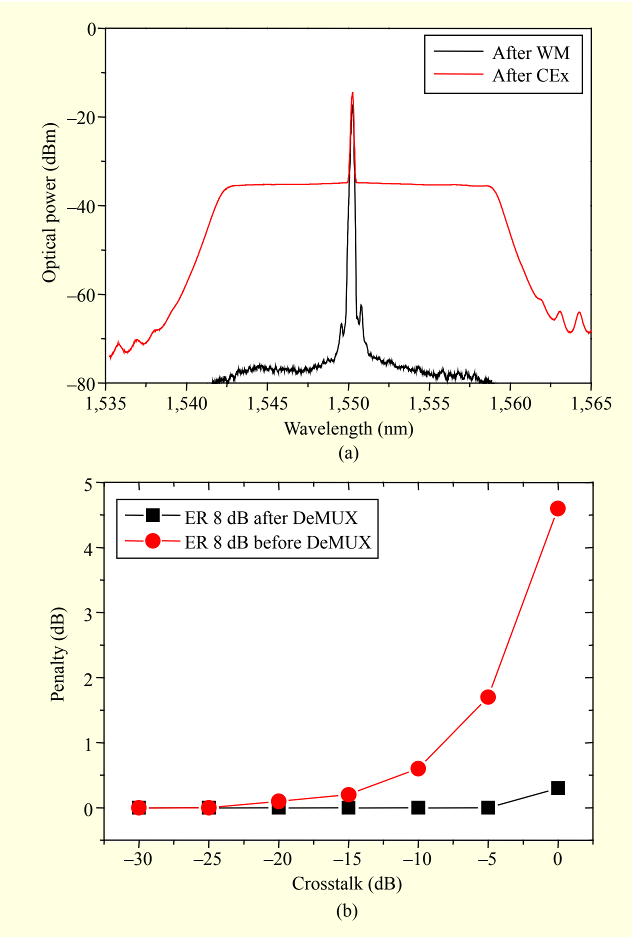


Fig. 10. (a) Output spectra before and after WM and (b) IC-induced power penalty as function of IC.

IV. Conclusion

We investigated the uplink IC-induced power penalty caused by ASE noise both in an XG-PON and in a TWDM-PON. Little attention has been paid to IC in time-division multiplexing passive optical networks. However, large IC caused by ASE noise degrades the upstream transmission performance in an XG-PON. Because of the 15 dB of DPL and the number of ONUs, which is as many as 256, the IC-induced power penalty is not negligible, and it should be considered when a PON system is designed. The experiment and simulation results indicate that optical filtering at the OLT is a simple and preferable way to reduce the IC. In the TWDM-PON case, the transmission performance was not degraded by the ASE-induced IC, because the ASE noise was filtered by the WM at the OLT. These results provide implementation guides for the ASE noise level of ONU transmitters of an XG-PON and a TWDM-PON. For future research, an investigation of the IC between the upstream signals of a TWDM-PON and P-t-P WDM-PON under a scenario of co-existence is advised.

References

[1] ITU-T Rec. G989.1, "40-Gigabit-Capable Passive Optical Networks (NG-PON2): General Requirements," 2013.

[2] ITU-T Rec. G989.2, "40-Gigabit-Capable Passive Optical Networks 2 (NG-PON2): Physical Media Dependent (PMD) Layer Specification," 2014.

[3] ITU-T Rec. G989.3, "40-Gigabit-Capable Passive Optical Networks 2 (NG-PON2): Transmission Convergence (TC) Layer Specification, Under Study," 2015.

[4] D. Iida et al., "Dynamic TWDM-PON for Mobile Radio Access," *Opt. Exp.*, vol. 21, no. 22, 2013, pp. 26209–26218.

[5] N. Cheng et al., "Flexible TWDM PON System with Pluggable Optical Transceiver Modules," *Opt. Exp.*, vol. 22, no. 2, 2014, pp. 2078–2091.

[6] H. Yang et al., "ONU Migration in Dynamic Time and Wavelength Division Multiplexed Passive Optical Network (TWDM-PON)," *Opt. Exp.*, vol. 21, no. 18, 2013, pp. 21491–21499.

[7] S. Ihara et al., "Experimental Demonstration of C-Band Burst-Mode Transmission for High Power Budget (64-Split with 40 km Distance) TWDM-PON Systems," presented at the *Conf. Opt. Commun.*, London, UK, Sept. 22–26, 2013, pp. 1–3.

[8] S.-G. Mun et al., "Wavelength Initialization Employing Wavelength Recognition Scheme in WDM-PON Based on Tunable Lasers," *Opt. Fiber Technol.*, vol. 21, Jan. 2015, pp. 141–145.

[9] J. Kim et al., "Physical Media Dependent Prototype for 10-Gigabit-Capable PON OLT," *ETRI J.*, vol. 35, no. 2, Apr. 2013, pp. 245–252.

[10] Calix, "Burst Extinction Ratio Requirements," FSAN Bad Nauheim Meeting, Aug. 2013.

[11] H.H. Lee et al., "Investigation on Burst-Mode Inter-Channel Crosstalk in XG-PON and TWDM-PON," presented at the *Opt. Fiber Commun. Conf.*, Los Angeles, CA, USA, 2014.

[12] H.Y. Rhy et al., "Inter-Channel Crosstalk Impairment of Time and Wavelength Division Multiplexing Passive Optical Network," presented at the *European Conf. Opt. Commun.*, London, UK, Sept. 22–26, 2013, pp. 1–3.

[13] F. Liu, C.J. Rasmussen, and R.J.S. Pedersen, "Experimental Verification of a New Model Describing the Influence of Incomplete Signal Extinction Ratio on the Sensitivity Degradation due to Multiple Interferometric Crosstalk," *Photon. Technol. Lett.*, vol. 11, no. 11, Jan. 1999, pp. 137–139.

[14] G.P. Agrawal, "Optical Receivers" in *Fiber-Optic Communication Systems*, New York, USA: Willey, 2010, pp. 133–178.

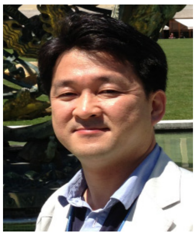
[15] M. Abramowitz and I.A. Stegun, Eds., "*Handbook of Mathematical Functions*," New York, USA: Dover, 1970.

[16] ITU-T Rec. G987.2, 10-Gigabit-Capable Passive Optical Networks (XG-PON): Physical Media Dependent (PMD) Layer Specification, 2010.

[17] ITU-T Rec. G984.5, Gigabit-Capable Passive Optical Networks (G-PON): Enhancement Band, 2014.

[18] W. Pöhlmann et al., "Low Cost TWDM by Wavelength-Set Division Multiplexing," *Bell Labs Techn. J.*, vol. 18, no. 3, 2013, pp. 173–193.

[19] N. Cheng et al., "Flexible TWDM PON with Load Balancing and Power Saving," presented at the *European Conf. Opt. Commun.*, Anaheim, CA, USA, 2013.



Han Hyub Lee received his BS, MS, and PhD degrees in physics from Chungnam National University, Daejeon, Rep. of Korea, in 1999, 2001, and 2005, respectively. His doctoral research included the application of a Raman fiber amplifier and gain-clamped SOA for WDM systems. From 2006 to 2007, he was a postdoctoral researcher at AT&T Laboratory, Middletown, NJ, USA, where he worked on extended WDM/TDM hybrid PONs using a wideband optical amplifier. In 2007, he joined ETRI as a senior researcher of the Department of Optical Internet Research. He has worked on optical access networks and has contributed to the development of international standardizations. He is a member of the IEEE.

Hee Yeal Rhy received his BS, MS, and PhD degrees from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Rep. of Korea, in 1993, 1995, and 1999, respectively. He spent two years at the Opto-Electronic Research Center at KAIST as a postdoctorate, from 1999 to 2002. He worked and served as an engineering director at a venture start-up company named Novera Optics, Daejeon, Rep. of Korea, from 2002 to 2008, where he developed products related with dynamic gain equalization EDFAs using acousto-optic tunable filters, optical component qualification systems, and WDM-PON systems. Since 2008, he has been an engineering team leader and principal research engineer at Ericsson-LG, Anyang, Rep. of Korea, where he has developed and researched optics products/solutions in access networks and contributed to ITU-T standardization. Recently, he is working on software-defined networks and network function virtualization. His research interests include optical access/metro networks, optical mobile backhaul/fronthaul, wavelength-division multiplexing technology, software-defined networking, and network virtualization.

Sangsoo Lee received his BS and MS degrees in applied physics and his PhD degree in the area of DWDM transmission technology from Inha University, Incheon, Rep. of Korea, in 1988, 1990, and 2001, respectively. Since 1990, he has been with ETRI, where he has been both a senior and principal member of the engineering staff. He is currently in charge of optical access technology development as a director. He has conducted research in 2.5 Gb/s, 10 Gb/s, and 40 Gb/s DWDM optical transmission and the ROADM system. For the past seven years, he has led high-level research on optical access technology, including WDM-PONs, NG-PON2, photonic integration, and wireless fronthaul. He is a member of the Optical Society of America. He has served as a technical committee member of both the Optical Fiber Communications Conference and the OptoElectronics and Communications Conference. He was a recipient of the Minister Award from the Korea Communications Commission in 2011 and the Best Researcher Award from the Korean government in 2013.

Jong Hyun Lee received his BS, MS, and PhD degrees in electronics engineering from Sungkyunkwan University, Suwon, Rep. of Korea, in 1981, 1983, and 1993, respectively. Since 1983, he has been with ETRI, where he has served as a director of both the Optical Communications Department and the Research Strategy & Planning Department. He was also an executive director of the Optical Internet Research Department. His current research interests include packet-circuit-optical converged switching systems, green IDC, and optical access networks.

Hwan Seok Chung received his PhD degree in electronics engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Rep. of Korea, in 2003. In 2003, he was a postdoctoral research associate with KAIST, where he worked on hybrid CWDM/DWDM systems for metro area networks. From 2004 to 2005, he was with KDDI R&D laboratories Inc., Saitama, Japan, where he was engaged in research on wavelength converters and regenerators. Since 2005, he has been with ETRI, where he is currently a director of the Optical Access Research Section. His current research interests include mobile fronthaul, high-speed PONs, and modulation formats. He has served as a technical committee member of OFC, OECC, COIN, ICOCON, and Photonic West. He was the recipient of the Best Paper Awards from the Optoelectronics and Communications Conference (OECC) in 2000 and 2003 as well as ETRI in 2011 and 2012. He is senior member of the IEEE.

http://dx.doi.org/10.4218/etrij.16.0115.0099