Maximum Reach of Long-Reach RSOA-Based WDM PON Employing Remote EDFA

U. H. Hong, K. Y. Cho, Y. Takushima, and Y. C. Chung
KAIST, Department of Electrical Engineering, 335 Gwahangno, Yuseong-gu, Daejeon 305-701, Korea
(Phone) +82-42-350-3456, (Fax) +82-42-350-3410, (E-mail) ychung@ee.kaist.ac.kr

Abstract: We investigate the effects of the gain and position of the remote EDFA in a long-reach RSOA-based WDM PON. Using this result, we also estimate the maximum transmission reach limited by Rayleigh backscattering.
OCIS codes: (060.2360) Fiber optics links and subsystems; (250.5980) Semiconductor optical amplifiers

1. Introduction

Recently, there have been many efforts to develop a long-reach wavelength-division-multiplexed passive optical network (WDM PON) for the purpose of extending the coverage of a central office (CO) [1]-[2]. On the other hand, for the cost-effective implementation of the WDM PON, it is indispensable to utilize the colorless light source such as the reflective semiconductor optical amplifier (RSOA). Thus, it would be highly desirable if we could realize the long-reach WDM PON by using RSOAs. However, since the RSOA-based WDM PON typically has a loopback configuration, its performance is vulnerable to the Rayleigh backscattering (RB) [3]-[5]. In particular, if we implement a long-reach RSOA-based WDM PON by using a remote Erbium-doped fiber amplifier (EDFA), its maximum reach can be seriously limited by RB (since it can also be amplified by the remote EDFA). Previously, we have investigated the optimum gain of this remote EDFA to minimize the penalty caused by RB [6]. However, this analysis is applicable only for the WDM PONs with fixed lengths of feeder and drop fibers. Thus, in this paper, we attempt to extend this analysis for the long-reach WDM PON with various lengths of feeder and drop fibers. For this purpose, we investigate the effects of the gain and position of the remote EDFA on the RB-induced degradation in the long-reach RSOA-based WDM PON operating at 1.25 Gb/s. We first classify the effects of the RB into two types and measure the penalties caused by these effects. We then calculate the RB-induced crosstalk levels as functions of the gain and position of the remote EDFA. The results show that there are optimum values for the EDFA's gain and position to minimize the RB-induced performance degradation. We also evaluate the RB-induced power penalties as a function of the transmission distance (i.e., link loss). The result shows that the allowable position of the remote EDFA becomes limited as the transmission distance is increased. In addition, the maximum reach of the RSOA-based WDM PON limited by RB is estimated to be ~100 km. We experimentally confirm these results by implementing a 100-km reach RSOA-based WDM PON operating at 1.25 Gb/s.

2. Effects of remote EDFA on Rayleigh backscattering in long-reach RSOA-based WDM PON

Fig. 1 shows the schematic diagram of the upstream link of a long-reach RSOA-based WDM PON implemented by using a remote EDFA. In this configuration, the RB signal can be generated from both the seed light and upstream signal. Thus, we classified the RB signal into two types; the backscattered seed light (RB-I) and the backscattered upstream signal (RB-II). If we define the crosstalk level as the power ratio of the RB signal to the upstream signal at the upstream receiver, the crosstalk level of RB-I and RB-II can be expressed as

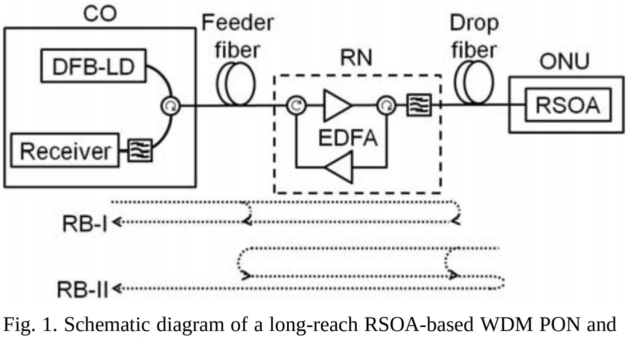

Fig. 1. Schematic diagram of a long-reach RSOA-based WDM PON and the directions of RB-I and RB-II.

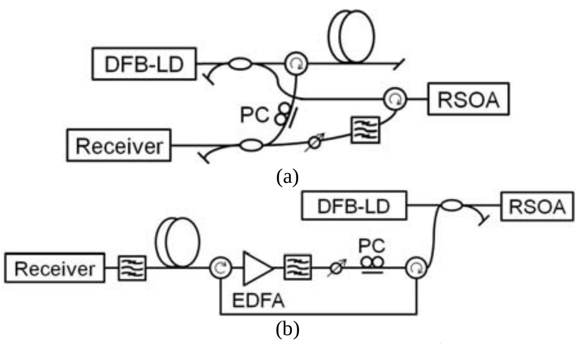

Fig. 2. Experimental setup to evaluate the impacts of (a) RB-I and (b) RB-II.

OMP1.pdf

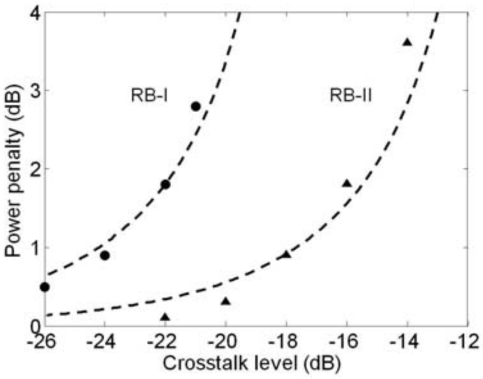

Fig. 3. RB-induced power penalties measured as a function of the crosstalk level.

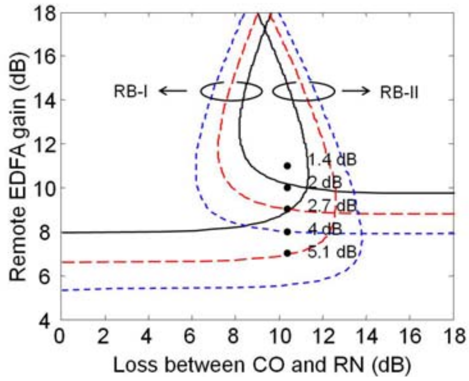

Fig. 4. Power penalties plotted as functions of the gain and position of the remote EDFA when the total link loss is 18 dB.

Crosstalk level of RB-I: $$l_f^{-2} l_d^{-2} R_f \,/\, G_{RSOA} G_{EDFA}^2 + l_d^{-2} R_d \,/\, G_{RSOA}\,, \tag{1}$$

Crosstalk level of RB-II: $$l_d^2 R_f G_{RSOA} G_{EDFA}^2 + R_d G_{RSOA}\,, \tag{2}$$

where $l_{f,d}$ are the losses of feeder and drop fiber (i.e., $l_{f,d}=\exp(-\alpha L_{f,d})$, where α is the fiber's loss coefficient and $L_{f,d}$ are the lengths of feeder and drop fiber), $G_{EDFA,RSOA}$ are the gains of remote EDFA and RSOA, and $R_{f,d}$ are the Rayleigh backscattered power ratios in the feeder and drop fiber (i.e., $R_{f,d}=B(1-l^2_{f,d})$), respectively, and B is the Rayleigh coefficient. For this calculation, we assume that the state-of-polarization (SOP) of RB is same with that of the upstream signal for the worst case analysis. The first term in (1) and (2) represents the crosstalk level induced by the RB generated in the feeder fiber, while the second term is originated from the RB generated in the drop fiber. To evaluate the impacts of RB-I and II on the bit-error rate (BER) performance of the upstream signal separately, we emulated the RB-I and II as shown in Fig. 2(a) and 2(b), respectively. For example, we can evaluate the impact of RB-I with no effect of RB-II in Fig. 2(a), and vice versa in Fig. 2(b). The upstream signal was obtained by modulating the RSOA with 1.25-Gb/s non-return-to-zero (NRZ) signal. Fig. 3 shows the power penalties (@ BER $=10^{-9}$) measured as a function of the RB-induced crosstalk level. For the worst case analysis, we adjusted the SOP of RB by using a polarization controller (PC). In this figure, the theoretical curves were obtained by assuming that the RB-induced MPI noises have Gaussian statistics [7]. The result showed that the impact of the RB-II induced crosstalk was less serious than that of RB-I. This was because the spectral width of the RB-II signal was broader than that of the RB-I signal (since the upstream signal was modulated while the seed light was unmodulated).

To investigate the effects of the gain and position of the remote EDFA on RB, we first calculated the crosstalk levels of RB-I and II using (1) and (2), respectively. We then estimated the power penalties caused by RB-I and II using these crosstalk levels and the experimental data in Fig. 3. Fig. 4 shows the results when the total link loss (i.e., the total loss between CO and ONU) was 18 dB. The solid, dashed, and dotted curves show the boundaries for the power penalties of 2, 3, and 4 dB, respectively. It is interesting to note that there exists the optimum remote EDFA position to minimize the power penalty. This is because the RB-I induced crosstalk level increases as the remote EDFA is placed closer to the CO (since the power of RB-I signal is drastically increased compared with the upstream signal when the feeder fiber is short). On the other hand, the RB-II induced crosstalk level is increased when the remote EDFA is placed closer to the ONU (since the power of RB-II signal is drastically increased compared with the upstream signal when the drop fiber is short). To verify this experimentally, we implemented a long-reach RSOA-based WDM PON shown in Fig. 1 and measured the RB-induced penalties. In this experiment, the lengths of the feeder and drop fibers were 50 and 40 km, respectively. The remote EDFA was made by using two unidirectional EDFAs, as shown in the dashed box in Fig. 1. In addition, we utilized PCs in the feeder fiber, EDFA, and drop fiber for the worst case measurement. The solid circles in Fig. 4 represent the measured power penalties, which agreed well with the estimated values by our model.

3. Maximum reach limited by Rayleigh backscattering in long-reach RSOA-based WDM PON

To mitigate the RB-induced performance degradations in the long-reach RSOA-based WDM PON, it is critical to properly determine the gain and position of the remote EDFA, as described in the previous section. Thus, we extended our analysis to include the transmission distance since it is one of the most important design parameters. Fig. 5 shows the power penalties plotted as functions of the total link loss and the position of the remote EDFA (i.e., the loss between CO and RN). For this analysis, we first estimated the optimum performance as a function of the

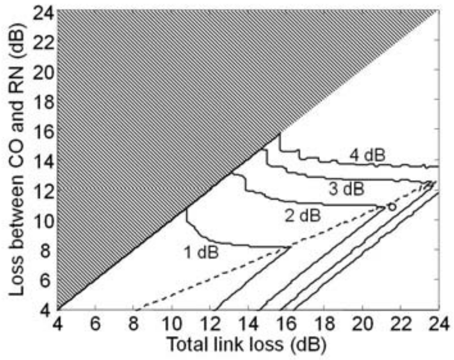

Fig. 5. Power penalties plotted as functions of the total link loss and the loss between CO and RN.

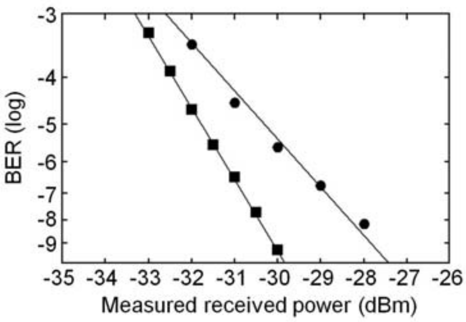

Fig. 6. Measured BERs in the back-to-back condition (squares) and in the case when the transmission loss is 21.6 dB (circles).

position of the remote EDFA for a fixed value of the total link loss, as in Fig. 4. We then repeated this estimation while varying the total link loss from 4 dB to 24 dB. The results are shown in Fig. 5. In this figure, the shaded area indicates the physically unavailable region (i.e., the remote EDFA should be placed outside of the transmission link in this region). The solid lines represent the boundaries of the RB-induced penalties in the range of 1 ~ 4 dB. The RB-induced penalty was increased as the total link loss (i.e., transmission distance) was increased. When the total link loss was <13 dB, we could suppress the RB-induced penalty to be <2 dB regardless of the position of the remote EDFA. However, if it is needed to further increase the maximum transmission distance (i.e., the total link loss: >13 dB), we should place the remote EDFA at a specific position to suppress the RB-induced penalty to be <2 dB. For example, if the total link loss is 18 dB, the remote EDFA should be placed at the position where the loss between CO and RN is in the range of 7 ~ 11 dB. This range is determined mainly by the fact that the effect of RB-I becomes severe when the remote EDFA is located close to the CO, while the effect of RB-II becomes severe when the remote EDFA is closely located to the ONU. The dashed line in Fig. 5 represents the optimum position of the remote EDFA to minimize the RB-induced power penalty. This result indicated that the EDFA's optimum position would be is at around the center of the total transmission link. To verify this estimation, we implemented the 100-km reach RSOA-based WDM PON (i.e., total link loss of 21.6 dB) shown in Fig. 1 and measured the RB-induced power penalty. The lengths of both feeder and drop fibers were set to be 50 km (i.e., the remote EDFA was placed at its optimum position). The results are shown in Fig. 6. The squares and circles represent the measure BERs in the back-to-back condition (i.e., no fiber and EDFA were used) and after 100-km long SMF transmission, respectively. The measured penalty of ~2.5 dB (i.e., represented by the open circle in Fig. 5) agreed well with the estimated value by our model.

4. Summary

We investigated the effects of the gain and position of the remote EDFA on the RB-induced degradations in a long-reach RSOA-based WDM PON. Using this result, we identified the optimum conditions of the remote EDFA (i.e., gain and position) to minimize the RB-induced power penalty. We also evaluate the RB-induced power penalty as a function of the total link loss. The results showed that the maximum reach could be increased to ~100 km by placing the remote EDFA at the center of the transmission link (assuming that the RB-induced penalty should be <2 dB).

5. References

[1] R. P. Davey et al., "Long-reach passive optical networks," *IEEE JLT*, vol. 27, no. 3, pp. 273-290, 2009.

[2] G. Talli and P. D. Townsend, "Hybrid DWDM-TDM Long-reach PON for next-generation optical access," *IEEE JLT*, vol. 24, no. 7, pp. 2827-2834, 2006

[3] M. Fujiwara, J. Kani, H. Suzuki, and K. Iwatsuki, "Impact of backreflection on upstream transmission in WDM single-fiber loopback access networks," *IEEE JLT*, vol. 24, no. 2, pp. 740-746, 2006.

[4] C. Arellano, K. Langer, and J. Prat, "Reflections and multiple Rayleigh backscattering in WDM single-fiber loopback access networks," *IEEE JLT*, vol. 27, no. 1, pp.12-18, 2009.

[5] E. T. Lopez, J. A. Lazaro, C. Arellano, V. Polo, and J. Prat, "Optimization of Rayleigh-limited WDM-PONs with reflective ONU by MUX positioning and optimal ONU gain," *IEEE PTL*, vol. 22, no. 2, pp. 97-99, 2010.

[6] U. H. Hong, K. Y. Cho, Y. Takushima, and Y. C. Chung, "Effects of Rayleigh backscattering in long-reach RSOA-based WDM PON," *OFC 2010*, Paper OThG1.

[7] G. P. Agrawal, *Fiber-Optic Communication Systems*, 3rd ed.(John Wiley & Sons, Inc., 2002), Chap. 4.