Effects of Rayleigh Backscattering in Long-Reach RSOA-Based WDM PON

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Abstract: We investigate the effects of Rayleigh backscattering in a long-reach RSOA-based WDM PON. The results show that the Rayleigh-induced penalty depends highly on the gain of the remote EDFA and the lengths of drop fibers.

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]. In such a long-reach WDM PON, a remote Erbium-doped fiber amplifier (EDFA) is often used to compensate for the losses of the transmission fiber and the remote node (RN). On the other hand, the WDM PON utilizing colorless light sources (such as reflective semiconductor optical amplifiers (RSOAs)) is typically implemented in a loopback configuration, in which the seed light and upstream signal operate at the same wavelength and travel in opposite directions within the same fiber [2]. Thus, the multipath interference (MPI), caused by the Rayleigh backscattering (RB) of the seed light and upstream signals, can result in the serious impairment of the transmission performance [3–5]. Previously, the effect of RB in a short-reach RSOA-based WDM PON (in which no remote EDFA is used) has been discussed in [6,7], including the dependence on the RSOA gain. However, this result cannot be applied to the long-reach WDM PON, since the RB signals generated in both the feeder and drop fibers are amplified by the remote EDFA and deteriorate the signal's quality.

In this paper, we investigate the effects of RB in a long-reach RSOA-based WDM PON operating at 1.25 Gb/s. In this network, we assume that a remote EDFA is used at the RN. We first classify the effects of RB into two types and calculate the RB-induced power penalties. We then experimentally evaluate these penalties as a function of the EDFA gain for various lengths of drop fibers. The theoretical and experimental results show that the RB-induced penalty is dependent on the EDFA gain and there is an optimum EDFA gain to minimize this penalty. However, since the optimum EDFA gain depends highly on the length of the drop fiber, it is almost impossible to accommodate various lengths of drop fibers simultaneously (even if we assume that the EDFA gain is adjustable). As a result, the design of long-reach WDM PONs can be seriously restricted by the MPI noise resulting from RB. To mitigate this problem, we examine the possibility of using an additional attenuator depending on the length of the drop fiber.

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

Fig. 1 shows a schematic diagram of the upstream link of a long-reach RSOA-based WDM PON implemented by using a remote EDFA. We assume that the cw seed light is sent to the RSOA in the optical network unit (ONU) from the CO. The upstream signal is obtained by directly modulating the RSOA. In this long-reach WDM PON, the upstream signal can interfere with the RB signals originating from both the seed light and upstream signals, which, in turn, results in the MPI noise. In addition, since the RB signals are amplified by the remote EDFA, the effects of RB are complex. To analyze these effects in details, we classify the RB signals into two types; the backscattered seed light (RB-I) and backscattered upstream signal (RB-II), as shown in Fig. 1. We analytically calculate the power of the RB signals reflected back to the CO by integrating the backscattered power along the

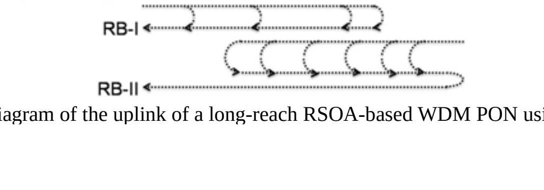

Fig. 1. A schematic diagram of the uplink of a long-reach RSOA-based WDM PON using a remote EDFA.

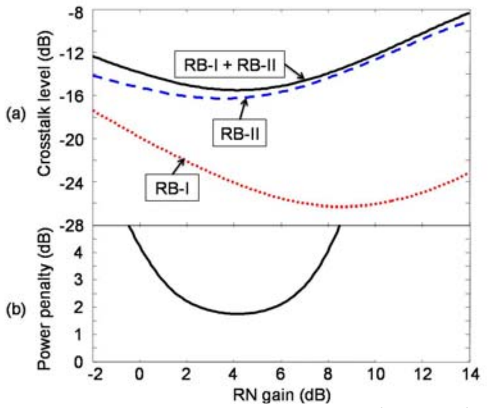

Fig. 2. (a) Crosstalk level and (b) power penalty as a function of the RN gain for 70-km long WDM PON (50-km feeder fiber and 20-km drop fiber).

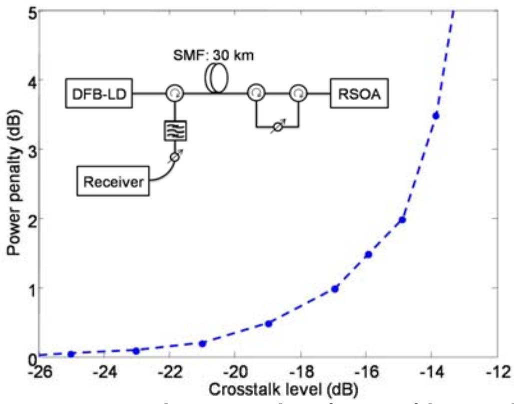

Fig. 3. Power penalties measured as a function of the crosstalk level caused by RB.

fiber link for RB-I and RB-II. For this calculation, we assume the use of conventional single-mode fiber (SMF) having the loss of 0.21 dB/km at 1550 nm. Fig. 2(a) shows an exemplary result obtained for the case when the feeder and drop fiber lengths are 50 km and 20 km, respectively. Here, to generalize the discussion for various combinations of the RN's loss and the EDFA gain, we define the RN gain as a sum of the EDFA gain and the loss of the AWG placed in the RN. We assume that the seed power at the CO is 2 dBm and the RSOA gain is 10 dB. The dotted and dashed curves show the crosstalk levels caused by RB-I and II, respectively. The results show that the RB-II is dominant since it is enhanced by the RSOA gain while the loss of the drop fiber is relatively small. The solid curve shows the total crosstalk level (which is the sum of the crosstalk levels of RB-I and RB-II). It is interesting to note that there is an optimum RN gain to minimize the crosstalk level. This is because the crosstalk level is worsened when the EDFA gain is very small (since the upstream signal becomes too small compared with the RB signal which does not pass through the remote EDFA). On the other hand, the crosstalk level is worsened when the EDFA gain is very high too (since the RB signal is increased drastically by the remote EDFA).

To evaluate the impact of the RB-induced crosstalk on the bit-error rate (BER) performance, we measured the power penalty (@ BER=10^{-9}) as a function of the crosstalk level (which was emulated by adjusting the power of upstream signal while using a constant power incident on the RSOA, as shown in the inset of Fig. 3). In this measurement, we used a 30-km long SMF to generate the RB signal and combined it with the upstream signal from the RSOA. Fig. 3 shows the measured power penalties as a function of the crosstalk level. The power penalty of 2 dB was observed at the crosstalk level of −15 dB, and it was drastically increased as the crosstalk level exceeded −14 dB. Using this experimental result together with the calculated crosstalk levels, we can estimate the power penalty caused by RB in a long-reach WDM PON. For example, Fig. 2(b) shows the estimated penalties corresponding to Fig. 2(a). In a similar manner, we can estimate the RB-induced power penalties for various configurations (i.e., different lengths of feeder and drop fibers) of long-reach WDM PONs.

3. Experiments and results

Fig. 4 shows the experimental setup to evaluate the impact of RB in a long-reach RSOA-based WDM PON. We used a distributed feedback (DFB) laser operating at 1550.8 nm at the CO for the seed light. At the ONU, the seed light was amplified and modulated by the RSOA with a 1.25-Gb/s non-return-to-zero (NRZ) signal (pattern length: 2^{31}−1). The upstream signal was sent back to the upstream receiver placed at the CO. We used an optical bandpass filter (OBPF) (3-dB bandwidth: 1 nm) located at the RN instead of the arrayed waveguide grating (AWG) for the experimental convenience. To secure a sufficient power budget, we used a bi-directional EDFA having

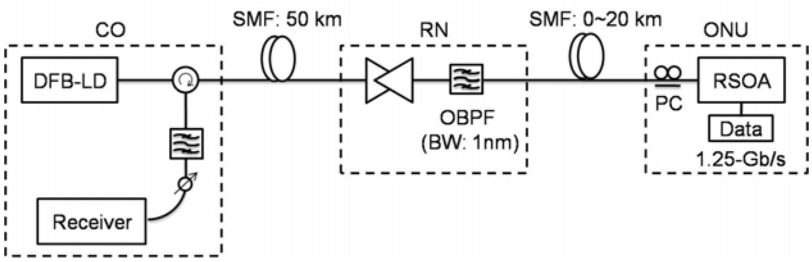

Fig. 4. Experimental setup.

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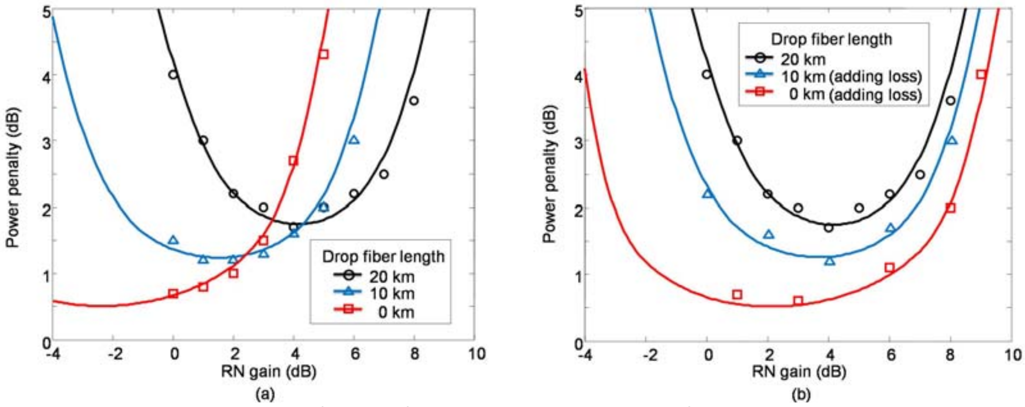

Fig. 5. Power penalty caused by RB as a function of RN gain while varying the drop fiber length (a) without the additional loss and (b) with the additional loss.

symmetric gains at the RN. The feeder fiber was 50-km long SMF with loss of 0.21 dB/km. We measured the power penalty (@ BER=10^{-9}) in comparison with the back-to-back receiver sensitivity (i.e., the case without using the transmission fiber and remote EDFA) as a function of the RN gain while changing the length of the drop fiber. Fig. 5(a) shows the results. The squares, triangles, and circles show the measured power penalties when the drop fiber lengths are 0, 10, and 20 km, respectively. The result was not sensitive to the state of polarization of the upstream signal. For comparison, we also showed the analytically calculated results by using the theory in the previous by using solid curves. The experimental results agreed well with the theoretically calculated results, indicating that we could predict the effect of RB by using the crosstalk level only.

It should be noted that the optimum RN gain needed to achieve the lowest power penalty depended highly on the drop fiber length. However, it would not be practically possible to adjust the drop fiber lengths (losses) and minimize the RB-induced power penalty. For example, if we optimized the RN gain for the 20-km long drop fiber (to be 4.5 dB), the signal from an ONU located in the vicinity of the RN (i.e., the length of the drop fiber is ~0 km) could suffer from a severe penalty. Thus, the RN gain should be adjusted to compromise the penalties for various lengths of drop fibers (i.e., set the RN gain to be ~3 dB in Fig. 5(a)). However, due to the extremely narrow operable range, a slight change in the EDFA gain could result in a serious penalty. To cope with this problem, we intentionally inserted an optical attenuator in the paths of the short drop fibers and adjusted the losses between the RN and ONU to be equal for every ONU. For a demonstration, we measured the power penalties after inserting 4-dB and 2-dB optical attenuators in the paths of the 0-km and 10-km long drop fibers, respectively (so that the total losses were identical regardless of the lengths of drop fibers). Fig. 5(b) shows the measured power penalties in comparison with the theoretically calculated curves. The optimum RN gain was increased as well as its operable range by using the additional optical attenuator. Thus, by using this technique, the network could be designed to accommodate various lengths of drop fibers without suffering the RB-induced power penalties.

4. Summary

We have investigated the effects of the RB on the upstream signal in a long-reach RSOA-based WDM PON implemented by using a remote EDFA. We found that the RB-induced penalty was strongly dependent on the RN gain and there existed an optimum RN gain to minimize the penalty. Since the optimum RN gain depended highly on the length of the drop fiber, it was practically not possible to simultaneously accommodate different lengths of drop fibers. To solve this problem, we utilized additional optical attenuators in the paths of short drop fibers to maintain the losses between the RN and ONU to be about the same regardless of the location of the ONU. By using this technique, we demonstrated that the long-reach WDM PON could accommodate drop fibers in the range of 0 ~ 20 km without suffering excessive penalties caused by RB.

5. References

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