Optical Fiber Technology 16 (2010) 129–134

Contents lists available at ScienceDirect

Optical Fiber Technology

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Improving upstream transmission performance using a receiver with decision threshold level adjustment in a loopback WDM-PON

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ARTICLE INFO

Article history:
Received 7 May 2009
Revised 16 December 2009
Available online 26 March 2010

Keywords:
Wavelength division multiplexing-passive optical network
Reflective semiconductor optical amplifier
Remodulation scheme
Decision threshold level adjustment

ABSTRACT

We have experimentally demonstrated that the use of an optical receiver with decision threshold level adjustment (DTLA) improved the performance of an upstream transmission in reflective semiconductor optical amplifier (RSOA)-based loopback wavelength division multiplexing-passive optical network (WDM-PON). Even though the extinction ratio (ER) of the downstream signal was as much as 9 dB and the injection power into the RSOA at the optical network unit was about −24 dBm, we successfully obtained error-free transmission results for the upstream signal through careful control of the decision threshold value in the optical receiver located at optical line terminal (OLT). Using an optical receiver with DTLA for upstream signal detection overcame significant obstacles related to the injection power into the RSOA and the ER of the downstream signal, which were previously considered limitations of the wavelength remodulation scheme. This technique is expected to provide flexibility for the optical link design in the practical deployment of a WDM-PON.

1. Introduction

The explosive growth of the demand for data and multimedia services has led to the deployment of broadband access equipment for fiber-to-the-home (FTTH) networks [1]. A promising approach for implementing FTTH networks is the use of wavelength division multiplexing-passive optical networks (WDM-PONs) [2]. One practical WDM-PON implementation that has been proposed for use in wavelength-independent optical network units (ONUs) involves a remodulation scheme whereby the optical upstream signal is generated by modulation over the incoming optical downstream signal [3,4]. The reflective semiconductor optical amplifier (RSOA) has attracted much attention as an excellent remodulator [5]. The upstream transmission performance of this type of loopback link is very sensitive not only to the injection power into the RSOA but also to the extinction ratio (ER) of the optical downstream data injected into the RSOA [4,6,7]. This is because the downstream signal cannot be perfectly erased from the gain saturation characteristic of the RSOA, resulting in a thickened 1 level of the optical upstream signal [8]. Achieving error-free upstream transmission for a given RSOA saturation characteristic and allowable link power budget imposes an upper limit on the downstream ER, which in turn results in a significant additional power penalty to the downstream transmission.

As directly modulated chirped light passes through concatenated WDM filters, it changes its ER due to selective spectral filtering that depends on the chirping characteristics, the detuned frequency, and the filter shape [9,10]. Lee et al. proposed a feed-forward current injection (FFCI) technique for optical wavelength-reuse without any gain saturation constraint [11]. They showed that the proposed technique could be used for a relatively low injection power into the RSOA at the ONU, thereby increasing the flexibility of the optical link design, free from the constraint of any power budget.

Such spectral filtering effects and FFCI techniques could be used to improve the upstream transmission performance in a loopback WDM-PON by suppressing the ER of the optical downstream signal that is eventually converted into 1 level fluctuation of the optical upstream signal over its loopback path. However, the ER of the downstream signal still must be restricted to less than 6 dB, which has been an obstacle to the practical deployment of WDM-PONs [3,11].

In this paper, we present the use of an optical receiver with decision threshold level adjustment (DTLA) in a loop-back WDM-PON. This dramatically reduces the upstream power penalty caused by the wavelength remodulation scheme and allows error-free transmission for a higher ER (about 9 dB) of downstream signal and much lower injection power into the RSOA (about −24 dBm).

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doi:10.1016/j.yofte.2010.01.004

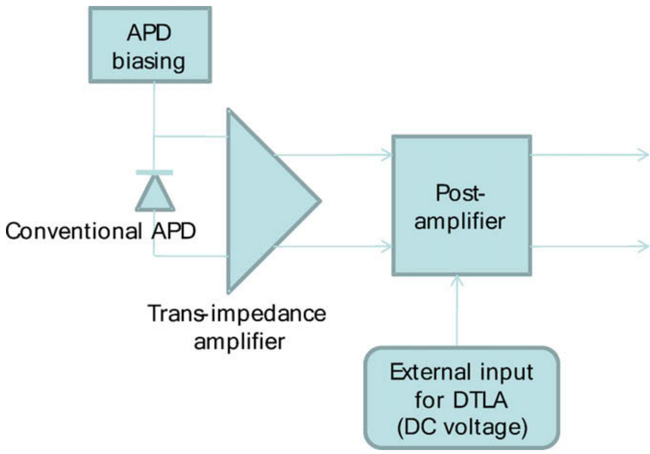

Fig. 1. Block diagram of the optical receiver with DTLA.

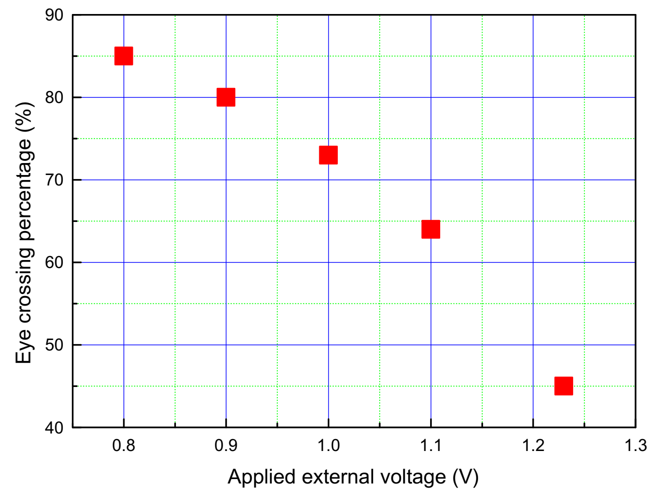

Fig. 2. Eye-crossing point as a function of applied external voltage value.

2. Receiver with DTLA in WDM-PON

Fig. 1 shows a block diagram of the optical receiver with DTLA used at the optical line terminal (OLT) to improve the upstream transmission performance. The optical receiver with DTLA consists of a conventional avalanche photo diode (APD), a commercial trans-impedance amplifier (TIA) and a post amplifier. In this configuration, the linear signal from the TIA can contain significant amounts of noise unevenly distributed between the 1 and the 0 levels, caused by the residual downstream components included in the optical upstream signal for the wavelength-reuse scheme [8,11]. In such noisy conditions, the decision threshold level between the 1 and the 0 levels must be moved to a level that contains less noise to optimize the bit error rate (BER) for the upstream signal [12].

In the following discussion, we introduce the concept of DTLA in optical receivers mathematically and present some experimental procedures for optimizing the decision threshold level related to the external electrical voltage input [13–15]. The decision threshold level γ is defined as the threshold value that results in the lowest probability of bit error.

$$\gamma = \frac{V_1(t)\sigma_0 + V_0(t)\sigma_1}{\sigma_0 + \sigma} \tag{1}$$

Eq. (1) shows that the optimized decision threshold value is one half for the ideal system (i.e., $\sigma_0 = \sigma_1$, $V_0(t) = 0$, and $V_1(t) = 1$). When σ_1 is much larger than σ_0 and $V_0(t)$ is fixed at 0, the optimized decision threshold value must be decreased to less than 1/2. Actually, the decision threshold level is seen as an eye-crossing percentage in the electrical signal that is the output of the post amplifier. If we are able to adjust the decision threshold level for the receiver, the eye-crossing percentage in the electrical signal moves up and down in the measured electrical-eye diagram.

An external voltage can be applied to a particular pin of the post amplifier used in this research to change the decision threshold level and optimize the BER performance. The change in the decision threshold level caused by applied different external voltage values results in a change in the electrical eye-crossing percentage, as shown in Fig. 2. Varying the external DC voltage input from 0.8 to 1.23 V changes the crossing of the output electrical signal from the post amplifier from 45% to 85% in the normal optical link. A distributed feedback laser-diode-based optical transmitter and our optical receiver with DTLA were used for relatively accurate measurements of the eye-crossing percentage. To examine the effect on the eye-crossing percentage for various external voltage input levels, the optical eye crossing was set to near 50% and the received optical power was fixed at −15 dBm. It is important to note that the signal crossing in the electrical-eye diagram increases as the decision threshold level is reduced.

3. Experimental results and discussion

3.1. Experimental setup

Fig. 3 shows the experimental setup used to investigate the improvement in the upstream transmission performance using an optical receiver with DTLA at the OLT. The downstream optical signal was generated by direct modulation of an RSOA, into which a spectrally sliced amplified spontaneous emission was injected from a high-power erbium-doped fiber amplifier (HP-EDFA)-based broadband light source. The injection power of spectrally sliced light into the RSOA was set to 0 dBm (0 dBm/1 nm) to produce a high-quality downstream optical signal with low-relative-intensity noise and low jitter characteristics [16–18]. The spectral slicing bandwidth was approximately 1 nm, which corresponds to the 1-dB passband of the thin-film filter (TFF) as a wavelength demultiplexer at the OLT.

The channel spacing was 200 GHz (1.6 nm) and there were 1×16 TFF based WDM (de)multiplexers. The directly modulated downstream light was transmitted to the RSOA at the ONU passing through the wavelength multiplexer at the OLT, two circulators, the feeder fiber, and the demultiplexer at the remote node. The upstream optical signal was also generated from an RSOA at the ONU; however, in this case the modulated downstream optical signal was used as seed light for wavelength selection [3,4,7,9,11,12]. We used FFCI gain control to erase the residual downstream signal in the 1 level of the upstream signal to improve the quality of the upstream signal [11]. Hence, the downstream ER could still be increased up to 6 dB. The remodulated upstream optical signal was received at the APD-based optical receiver at the OLT. The modulation speed in both directions was 1.25 Gbps with independent non-return-to-zero signals. The pattern length was a pseudo-random binary sequence of length $2^7 - 1$, the closest match to Gigabit Ethernet signals with 8 B/10 B coding [3,4,19,20].

3.2. Eye-crossing percentage vs. decision threshold level

First, we measured the eye-crossing percentage in the electrical eye pattern from the optical receiver at the OLT to determine the optimized decision threshold level. To measure the eye-crossing

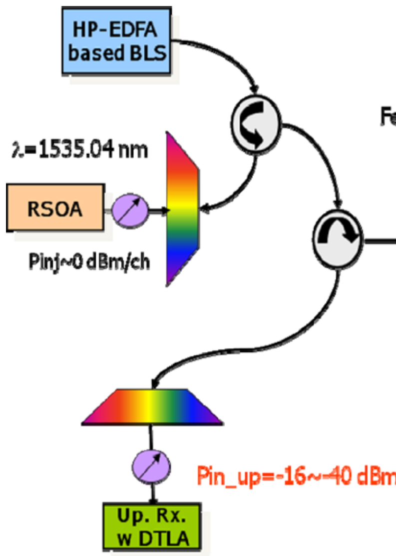

Fig. 3. Experimental setup to investigate the improvement in the upstream transmission performance using an optical receiver with DTLA at the OLT.

percentage, we set the injection power into the RSOA at the ONU to −17 dBm and input optical power for the optical receiver with DTLA to −20 dBm. We varied the external input voltage level that controlled the real decision threshold level over the range 0.7–1.2 V. The crossing point of the RSOA-based optical transmitter at the ONU was set to about 25%. Fig. 4 shows the measured electrical eye patterns and crossing percentages. An external voltage input fixed at 0.9 V resulted in the lowest peak-to-peak jitter value as well as a crossing level of about 50%, which produced the best upstream transmission performance.

Fig. 5 shows the measured electrical eye pattern for the remodulated upstream signal using the optical receiver with and without

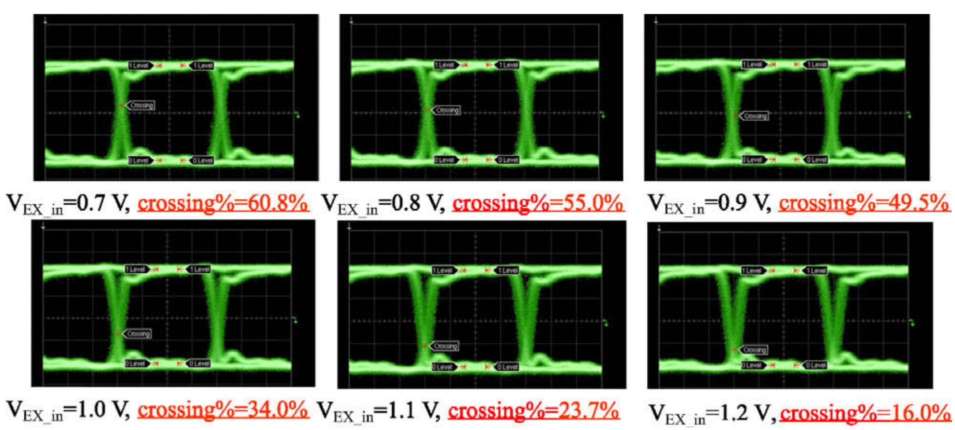

Fig. 4. Measured electrical eye pattern and crossing percentage value for various external voltage inputs.

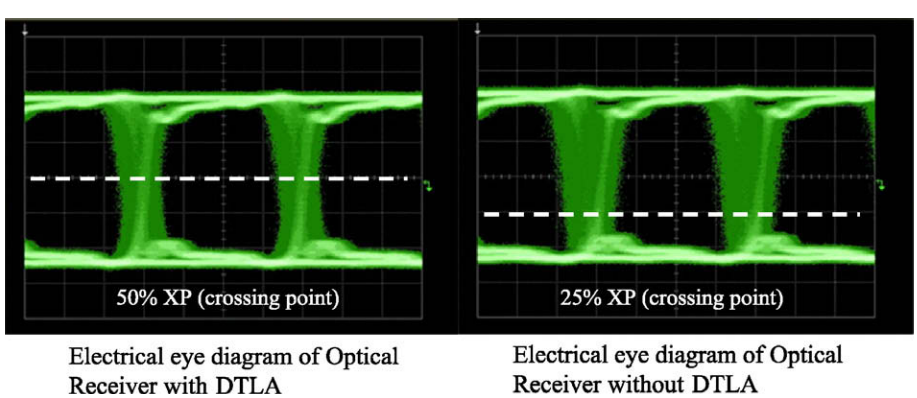

Fig. 5. Measured electrical eye pattern for the remodulated upstream signal using the optical receiver with and without DTLA.

DTLA in the loopback WDM-PON. Using the optical receiver with DTLA for detection of the upstream signal considerably reduced the peak-to-peak jitter values of the upstream signal. On the other hand, relatively thick pulse width distortion was observed when using the optical receiver without DTLA because of the higher decision threshold level in the optical receiver. The optical received power in these measurements was set to −25 dBm, the injection power into the RSOA at the ONU was −24 dBm, the ER of downstream light was about 6 dB, and the center wavelength of the signal was 1535.04 nm. We believe that the use of the optical receiver with DTLA permits dramatic improvement of the upstream transmission performance in an RSOA-based loopback WDM-PON, as shown by the measured electrical-eye diagram.

3.3. Transmission results for varying injection power into the RSOA

To compare the transmission performance of an optical receiver with DTLA with that of a conventional receiver (receiver without DTLA), we measured upstream BER values for various injection powers into the RSOA at the ONU. The results are shown in Fig. 6.

Similar to the previous measurement of the electrical eye pattern, the ER of downstream light was set to 6 dB, the center wavelength of the signal was 1535.04 nm, and the RSOA injection power level was varied from −16 to −24 dBm. The differences in receiver sensitivity were relatively small in the injection power range of −16 to −18 dBm because a conventional optical receiver was used for upstream signal detection. This is because the input saturation power of the TO-packaged RSOA used in our experiment was about −18 dBm. When the optical power injected into the RSOA was greater than −18 dBm, the residual ER components in the upstream signal were very small due to the ER-squeezing effects of the gain-saturated RSOA. However, the lower the injection power into the RSOA, the less suppressed the modulated downstream signal in the upstream transmission became, eventually degrading the BER performance of the upstream signal. In spite of the fact that the higher downstream ER of 6 dB and an injected power level less than the input saturation power of the RSOA were used as our experimental conditions, we achieved error-free transmission using the RSOA-based transmitter with FFCI gain control. We could have observed the error floor if we had not used that kind of transmitter at the ONU. Using the normal optical receiver at the OLT for upstream transmission resulted in a maximum power penalty of 8.5 dB for various injection power levels into the RSOA. On the other hand, using an optical receiver with DTLA resulted in a maximum power penalty of 3.5 dB for a much lower RSOA injection power of −24 dBm. Compared to the BER results measured using the normal receiver, we succeeded in reducing the difference in receiver sensitivity for a BER of 10^{-12} to 5 dB with an injection power of −24 dBm into the RSOA at the ONU. There were no significant differences in receiver sensitivity with or without DTLA when the RSOA injection power was well above the saturation point.

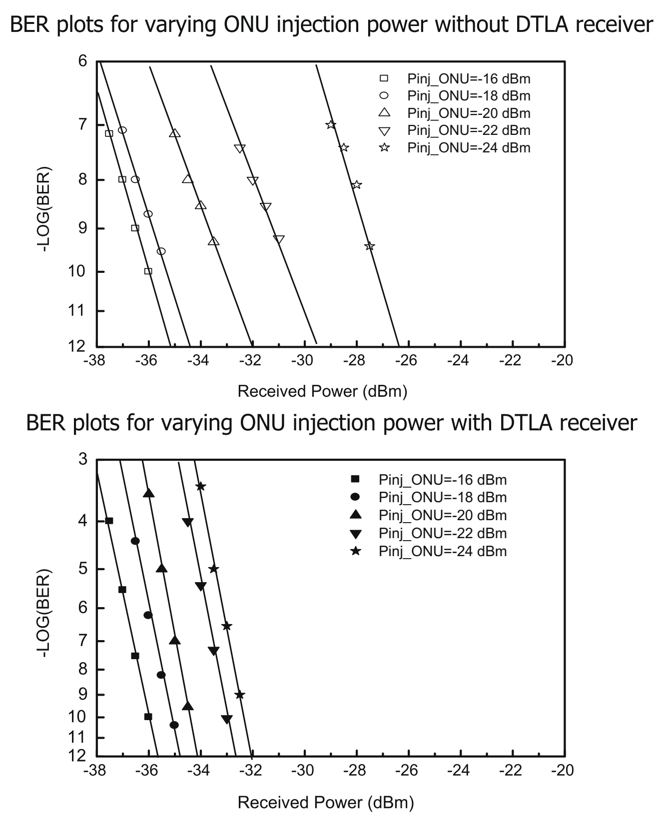

Fig. 6. Measured upstream BERs for different levels of injection power into the RSOA at the ONU.

3.4. Transmission results for varying ER of the downstream light

Fig. 7 shows the measured optical eye patterns for upstream transmission when the ER of the downstream signal increased from 6 dB to 10 dB while the injection power into the RSOA at the ONU was fixed at −18 dBm. The optical eye of the upstream signal closed gradually as the ER of the downstream signal increased. Fig. 7 shows that the use of an RSOA-based optical transmitter with FFCI gain control and the natural gain-squeezing effect of the RSOA itself were not sufficient to squeeze the amplitude noise in the 1 level to improve the upstream signal transmission. Several previous studies have reported that the maximum allowable ER of downstream light was about 6 dB in a loopback WDM-PON where on–off-keying modulation was used on the up- and downstream data [3,11]. In Fig. 7, a relatively closed eye was observed when the downstream ER was greater than 9 dB. With a downstream signal ER of about 10 dB, it was impossible to detect the upstream signal because of the thicker 1 level and the crossing point hidden behind the 1 level as shown by the dotted red circles.

Fig. 8 shows the electrical-eye diagrams for different values of the downstream signal ER measured to investigate the improvement of the upstream transmission performance using the receiver with DTLA. In these measurements, the injection power into the RSOA at the ONU was fixed at −18 dBm, the received optical power for the receiver was −25 dBm, and the ER of downstream light was

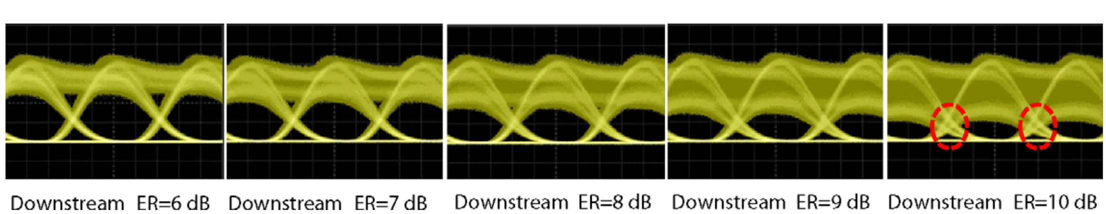

Fig. 7. Measured optical eye patterns for upstream transmission when the ER of the downstream signal increased from 6 dB to 10 dB.

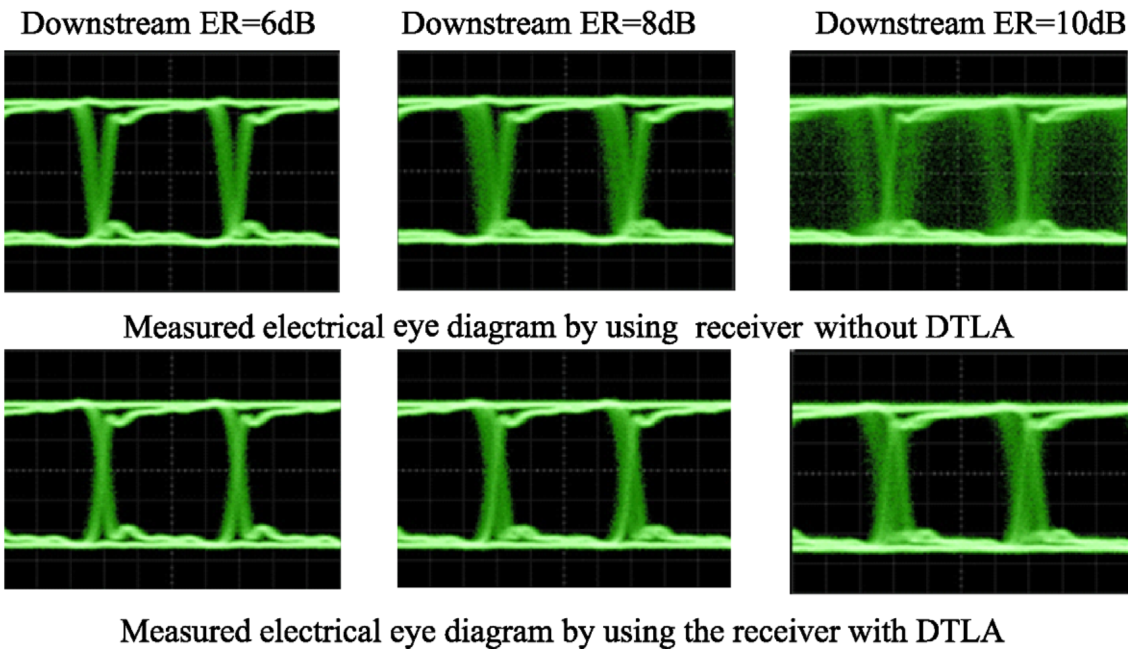

Fig. 8. Measured electrical-eye diagrams for various values of downstream signal ER.

varied over the range 6–10 dB. Using the normal receiver at the OLT, we were able to observe the lower eye-crossing point in the electrical eye patterns regardless of the ER of the downstream signal. Fig. 7 shows that the optical eye-crossing points were far below 50% (half of the eye amplitude). Those eye-crossing points were directly reflected in the electrical eye patterns. To minimize the degradation of the upstream transmission quality for residual ER components and to maximize the ER of the upstream signal, we set the eye-crossing point of the upstream signal remodulation to below 35% by appropriately controlling the bias and modulation current. For this purpose, the RSOA at the ONU was biased near the threshold current and modulated at twice the threshold current. However, we obtained an electrical eye-crossing point of about 50% using the optical receiver with DTLA, resulting in a better upstream transmission performance. This clearly showed that increased downstream ER generated a certain amount of jitter due to pulse width distortion. Such jitter effects always were existed for all the upstream signals for optical receivers with or without DTLA. However, when the optical receiver with DTLA was used for upstream signal detection, the electrical eye-crossing points reached nearly 50% and a relatively clear eye opening was shown when the decision threshold level was intentionally lowered. Even if the ER of the downstream signal was as high as 10 dB, it might be possible to obtain an open electrical-eye diagram using a receiver with DTLA.

We also investigated the effect of the downstream ER on the BER characteristics for upstream transmission to verify the performance of an optical receiver with DTLA. Using the normal receiver, we were able to achieve error-free upstream transmission with a downstream ER of up to 7 dB. Fig. 9 shows that the power penalty was larger for larger ER values, and the error floor occurred at a downstream ER of 8 dB. In contrast, we obtained error-free transmission with a downstream ER of up to 9 dB when the receiver with DTLA was used at the OLT. The sensitivity difference between ER values of 6 dB and 9 dB was within 2 dB. Under the same overall conditions for the ER of the downstream signal, we confirmed that the optical receiver with DTLA improved the upstream transmission performance dramatically.

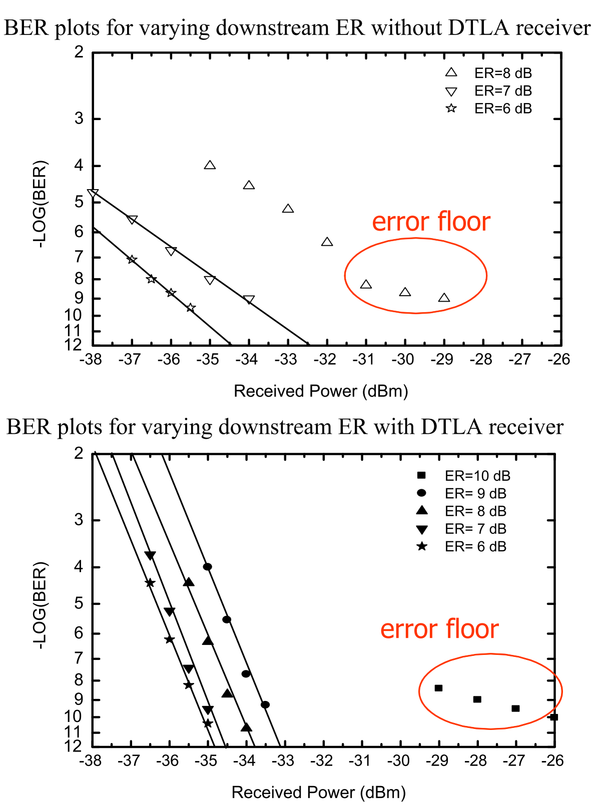

Fig. 9. Measured BER plots for various values of downstream signal ER.

4. Conclusion

We have experimentally demonstrated that upstream transmission performance was improved by an optical receiver with DTLA in an RSOA-based loopback WDM-PON. The decision threshold level to optimize the upstream BER was set to a typical voltage value through a special procedure whereby the threshold level was empirically converted to the eye-crossing percentage of the electrical-eye diagram. After the decision threshold level was fixed in the optical receiver, we measured the upstream BERs and eye patterns for various injection powers into the RSOA at the ONU and for various ER values of downstream light. The same measured results with the conventional optical receiver were presented for comparison. For an optical receiver using DTLA, an upstream power penalty of 3.5 dB occurred for an RSOA injection power of −24 dBm. In addition, we achieved error-free upstream transmission with a 1.6-dB power penalty, even though the ER of the downstream signal was as high as 9 dB. On the other hand, as the injection power into the RSOA decreased to −24 dBm, it was possible to obtain error-free upstream transmission with an 8.5-dB power penalty using a normal receiver. We also confirmed that the error floor phenomena occurred when the ER of the downstream light was in excess of 7 dB. Our investigation definitely showed the effectiveness of a receiver with DTLA in an RSOA-based loopback WDM-PON system.

Acknowledgments

The authors would like to thank Dr. B. W. Kim, Dr. M. Y. Park, Dr H.H. Lee, and Mrs. J. H. Lee for their helpful discussions. This work was supported by the IT research and development program of the Korean Ministry of Knowledge Economy/Institute for Information Technology Advancement (2007-S014-02, Metro Access Integrated Optical Network Technology).

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