Effects of External Optical Feedback on PAM4 Signal in VCSEL-Based SMF Link

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***Abstract*— We evaluate the effects of the external optical feedback on the on-off keying (OOK) and four-level pulse amplitude modulation (PAM4) signals in the single-mode fiber (SMF) link implemented by using a commercial 10G-class 1.55-μm vertical-cavity surface-emitting laser (VCSEL). The results show that the PAM4 signal is much more sensitive to the external optical feedback than the OOK signal. For example, in the back-to-back condition, an error floor is observed at the bit-error rate (BER) of ~8×10^{-3} for the 10-Gbaud PAM4 signal when we set the optical feedback ratio to be −14 dB. In comparison, the 10-Gbaud OOK signal has a power penalty of only 0.4 dB (@BER = 5×10^{-5}) under the same conditions. The results also show that the PAM4 signal becomes more sensitive to the optical feedback after the SMF transmission due to the shallowed BER curve by the fiber dispersion. In addition, we confirm that the effects of the optical feedback are independent of the baud rate. From these results, we conclude that the error-free transmission of the high-speed PAM4 signal cannot be achieved if there is even one bad fiber connector having >2.5% reflection in the VCSEL-based SMF link.**

***Index Terms*— Optical feedback, relative intensity noise, pulse amplitude modulation, vertical-cavity surface-emitting laser.**

I. Introduction

Vertical-cavity surface-emitting laser (VCSEL) is widely used in various short-haul applications due to its low cost, low power consumption, and small size. However, the VCSEL-based transmitters are exposed to the external optical feedback with no protection since they are typically manufactured without optical isolators. It is well known that the external optical feedback can increase the relative intensity noise (RIN) and broaden the optical spectral width of the semiconductor laser [1], [2]. It has also been reported that the VCSEL has a similar sensitivity to the external optical feedback with the edge-emitting laser [2]. Nevertheless, the power penalty caused by the optical feedback in the VCSEL-based single-mode fiber (SMF) link is reported to be relatively small (i.e., typically <2.5 dB at the bit-error rate (BER) of 10^{-9} even when there is a bad fiber connector having 4% reflection) [3]–[6]. We attribute this to the facts that the VCSEL link has mostly utilized the on-off keying (OOK) format so far (which is quite robust against the RIN) and the broadened optical spectrum does not seriously increase the dispersion penalty in the short-haul system operating at a relatively low speed. As a result, it appears that the external optical feedback has been considered to be not a major problem in the VCSEL-based link since the small power penalty can be taken care of by the ample power budget in the short-haul system. However, the four-level pulse amplitude modulation (PAM4) has recently become the most popular format for the development of the ultrahigh-speed (>50 Gb/s) short-haul system [7]. Yet, to the best of our knowledge, there has been no report on the effects of the optical feedback on the PAM4 signal in the VCSEL-based SMF link. Thus, in this letter, we investigate this problem by comparing the BER performances of the OOK and PAM4 signals generated by using a 1.55-μm VCSEL in an SMF link under the influence of the external optical feedback. The results show that, as expected, the PAM4 signal is much more sensitive to the external optical feedback than the OOK signal. For example, when we set the optical feedback ratio to be -14 dB (which can be caused by a bad fiber connector), an error floor is observed at the BER of $\sim 8.0 \times 10^{-3}$ in the back-to-back condition for the 10-Gbaud PAM4 signal, while the OOK signal operating at the same baud rate has a power penalty of only 0.4 dB (@BER = 5×10^{-5}) under the same condition. The results also show that the PAM4 signal becomes more sensitive to the external optical feedback after the SMF transmission (since the BER curve is shallowed by the fiber dispersion). For example, after the transmission over 2.4 km of SMF, an error floor is observed at the BER of $\sim 1.3 \times 10^{-2}$ for the 10-Gbaud PAM4 signal when we set the optical feedback ratio to be −14 dB. In comparison, there is no significant difference in the measured power penalties for the 10-Gbaud OOK signal before and after the 2.4-km long SMF transmission. We also measure the effect of the external optical feedback on the OOK and PAM4 signals operating at various baud rates (5, 7, 10, and 14 Gbaud), and confirm that it is independent of the baud rate.

II. Experiment and Results

The experimental setup to evaluate the effects of the external optical feedback on the OOK and PAM4 signals in a VCSEL-based SMF link is shown in Fig. 1(a). In this experiment, we utilized a commercial 10G-class 1.55-μm single-mode VCSEL packaged in a TO-can with an SMF pigtail (Vertilas GmbH, VL-1550-10G-P2-H4). The fiber-coupling efficiency of this VCSEL was estimated to be ~46% by measuring the relaxation oscillation frequency and the optical feedback ratio causing the coherence collapse [8]. Figure 1(b) shows

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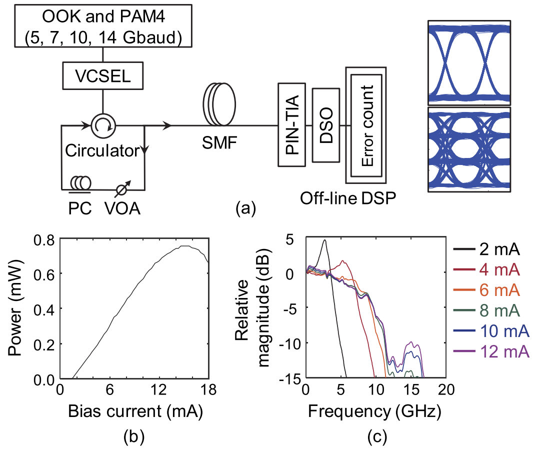

Fig. 1. (a) Experimental setup. (b) Measured L-I curve and (c) frequency response characteristics of the 1.55-μm VCSEL.

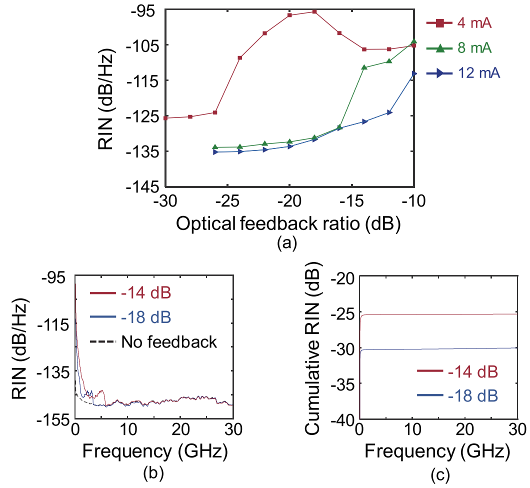

Fig. 2. (a) Measured RIN (averaged over 0-14 GHz) as a function of the external optical feedback ratio at various bias currents. (b) Measured RIN spectra and (c) cumulative RIN (obtained by integrating the RIN spectra in Fig. 2(b) from 30 MHz to an upper bound indicated by the x-axis) at two different optical feedback ratios of -14 dB and -18 dB.

the measured L-I curve of this VCSEL. The 3-dB bandwidth of this VCSEL was increased with the bias current, as shown in Fig. 1(c). However, it appeared to be saturated at $\sim$7.3 GHz when we increased its bias current to be higher than 6 mA. This was primarily due to the bandwidth-limited package used in this commercial 10G-class VCSEL. On the other hand, we noted that the use of the high bias current could also help reduce the RIN [1]. Thus, we set the bias current of this VCSEL to be as high as 12 mA, and then generated the OOK and PAM4 signals operating at 5, 7, 10, and 14 Gbaud (pattern length: 2^{15}-1). The insets in Fig. 1(a) show the eye diagrams of the 5-Gbaud OOK and PAM4 signals measured in the back-to-back condition with no external optical feedback. The extinction ratios (ERs) of these OOK and PAM4 signals were set to be 8 dB. However, it should be noted that, when we increased the bias current of this VCSEL to be higher than 12 mA, it was not possible to generate the equally spaced PAM4 signal having an ER of 8 dB due to the saturation of its output power. Thus, we could not increase the bias current to be higher than 12 mA. To evaluate the effects of the external optical feedback, we sent a portion of the signal back to the VCSEL by using an optical circulator (return loss: $>$60 dB). The polarization state of this optical feedback signal was adjusted to maximize the RIN by using a polarization controller (PC). We detected the modulated signals by using a PINFET receiver (3-dB bandwidth: 33 GHz), while varying the optical feedback ratio by using a variable optical attenuator (VOA). These modulated OOK and PAM4 signals were sampled by using a digital storage oscilloscope (DSO) at 50 Gsample/s (3-dB bandwidth: 20 GHz). We then processed the sampled data offline and counted the errors directly.

It is well known that the optical feedback can degrade the RIN and spectral width of the semiconductor laser [1]–[2]. Thus, we first measured the RIN and optical spectrum of the 1.55-μm VCSEL as a function of the external optical feedback ratio at various bias currents. Figure 2(a) shows the measured RIN averaged over 0-14 GHz. As expected, the RIN was decreased as we increased the bias current. This was because the critical feedback ratio (which indicated the onset of the coherence collapse) was increased by the increased relaxation oscillation frequency [1], [9]. We also confirmed from Fig. 2(a) that the RIN increased with the external optical feedback. In particular, the RIN increased suddenly when the optical feedback ratio was increased to be higher than the critical feedback ratio. For example, when we set the bias current to be 12 mA, the RIN was drastically increased at the optical feedback ratio of >-12 dB (which agreed well with the calculated critical feedback ratio of -12 dB, assuming that the linewidth enhancement factor, cavity length, fiber-coupling efficiency and facet reflectivity of the VCSEL were 4, 2 μm, 46%, and 0.998, respectively). We also noted that the effects of the external optical feedback on the RIN became independent of the bias current when it was increased to be higher than 12 mA (due to the saturation of the relaxation oscillation frequency at the high bias current). We measured the RIN spectra at two different optical feedback ratios of -14 and -18 dB and obtained the cumulative RIN, as shown in Figs. 2(b) and 2(c), respectively. In these figures, the minimum RIN (that could be measured) was -167 dB/Hz. In the presence of the external optical feedback, most of the RIN was measured to be in the low-frequency region, as shown in Fig. 2(b) [10]. As a result, the cumulative RIN was almost unvarying (i.e., not dependent on the frequency), as shown in Fig. 2(c). Thus, we predicted that the performance degradation caused by the increased RIN (due to the increased external optical feedback) would be the same regardless of the baud rate if there were no other source of impairments.

Figure 3 shows the optical spectra of the unmodulated VCSEL measured with and without the external optical feedback. The effect of the optical feedback on the VCSEL's optical spectrum was also strongly dependent on the bias current. For example, when we set the bias current to be 4 mA, the optical spectrum was broadened significantly at the optical feedback ratio of -14 dB, as shown in Fig. 3(a). However, this effect of the optical feedback on the laser's spectrum became gradually reduced as we increased the bias current. As a result, when we increased the bias current to be 12 mA, no noticeable spectral broadening was observed even at the optical feedback ratio of -14 dB, as shown in Fig. 3(b). We also measured the optical spectra of the 14-Gbaud PAM4 signals under the influence of the external

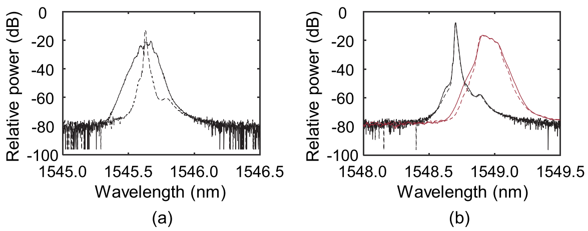

Fig. 3. Measured optical spectra of the unmodulated VCSEL with and without the external optical feedback when the bias current and optical feedback ratio were set to be (a) 4 mA and −14 dB and (b) 12 mA and −14 dB, respectively. In (b), the red lines represent the optical spectra of the VCSEL modulated with the 14-Gbaud PAM4 signal with and without the external optical feedback. In these figures, the dotted lines indicate the spectra of the VCSEL measured without the external optical feedback.

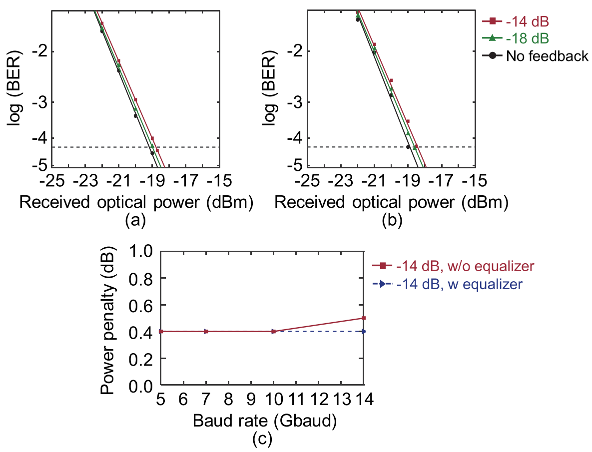

Fig. 4. Measured BER curves of the 10-Gbaud OOK signal at various optical feedback ratios (a) in the back-to-back condition and (b) after the 2.4-km long SMF transmission. (c) Measured power penalties of the OOK signal versus the baud rate in the back-to-back condition under the influence of the optical feedback ratio of −14 dB. In (c), the dashed line represents the power penalties measured with a 10-tap FFE.

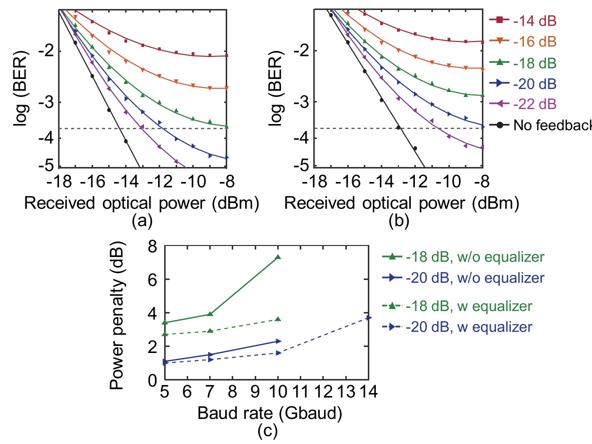

Fig. 5. Measured BER curves of the 10-Gbaud PAM4 signals at various optical feedback ratios (a) in the back-to-back condition and (b) after the 2.4-km long SMF transmission. (c) Measured power penalties of the PAM4 signal versus the baud rate in the back-to-back condition under the influence of the optical feedback ratios of −20 dB and −18 dB. In (c), the dashed lines represent the power penalties measured with a 10-tap FFE.

optical feedback. The results showed that the effect of the external optical feedback on the spectrum of the modulated signal was relatively insignificant. This was mainly because the optical spectrum of the directly modulated VCSEL was quite broad already even without the optical feedback due to its large chirp. For example, when we set the optical feedback ratio and bias current to be −14 dB and 12 mA, respectively, the spectral width of the 14-Gbaud PAM4 signal (ER: 8 dB) was broadened only slightly, as shown by the red lines in Fig. 3(b). Thus, we concluded that, under the influence of the external optical feedback, the performance of the directly modulated VCSEL link would be deteriorated mostly by the increased RIN rather than the broadened optical spectrum.

Figure 4(a) shows the measured BER curves of the 10-Gbaud OOK signal in the back-to-back condition under the influence of the external optical feedback. In the absence of the optical feedback, the receiver sensitivity of this 10-Gbaud OOK signal was measured to be −19.2 dBm (@BER $= 5 \times 10^{-5}$). (In the case of using the OOK format, we utilized this BER of 5×10^{-5} as a reference considering the use of the Reed-Solomon (528,514) forward-error-correction (FEC) code [11]). This figure also showed that, as expected, the power penalty was gradually increased with the optical feedback ratio. However, it was measured to be only ~0.4 dB for this 10-Gbaud OOK signal even when we increased the feedback ratio to be as large as −14 dB. Figure 4(b) shows the measured BER curves of this 10-Gbaud OOK signal after the transmission over 2.4 km of SMF. When there was no external optical feedback, the receiver sensitivity was measured to be −18.9 dBm. Thus, the power penalty caused by the fiber dispersion was estimated to be 0.3 dB. However, there was no significant difference in the power penalties (caused by the external optical feedback) measured before and after the SMF transmission. For example, when we set the optical feedback ratio to be −14 dB, the power penalty measured after the 2.4-km long SMF transmission was 0.4 dB (which was almost identical to the value obtained in the back-to-back condition). Thus, we concluded that the effects of the external optical feedback would not be a major concern in the VCSEL-based short-haul OOK system. We also confirmed that, as predicted earlier, the performance degradation caused by the increased RIN (due to the increased optical feedback) was not dependent on the baud rate of the signal. For example, Fig. 4(c) shows the power penalties (@BER $= 5 \times 10^{-5}$) measured in the back-to-back condition while varying the baud rate of the OOK signal from 5 to 14 Gbaud. In this experiment, the optical feedback ratio was set to be −14 dB. The results showed that the power penalty was nearly unchanged even if we increased the baud rate from 5 to 7 to 10 Gbaud. However, when we increased the baud rate to 14 Gbaud, the penalty was slightly increased (by ~0.1 dB) due to the limited bandwidth of the VCSEL. Thus, we could mitigate this additional penalty simply by applying a 10-tap feed-forward equalizer (FFE).

Figure 5(a) shows the measured receiver sensitivities of the 10-Gbaud PAM4 signal in the back-to-back condition while varying the optical feedback ratio. In the absence of the optical feedback, its receiver sensitivity was measured to be −14.4 dBm (@BER $= 2.4 \times 10^{-4}$). (In the case of using the PAM4 format, we utilized this BER of 2.4×10^{-4} as a reference considering the use of the Reed-Solomon (544,514) FEC code [7].) This sensitivity was 5.3 dB worse than that of the OOK signal measured at the same BER of 2.4×10^{-4}, which was in reasonable agreement with the theoretically calculated value of 4.8 dB [12]. We attributed the difference

(0.5 dB) to the fact that the effects of the limited bandwidth of the VCSEL would be more serious on the PAM4 signal than the OOK signal operating at the same baud rate. As expected, the PAM4 signal was measured to be much more sensitive to the external optical feedback than the OOK signal. In the case of PAM4 signal, error floors were observed as the BER curves became non-straight lines due to the increased RIN. For example, in the back-to-back condition, an error floor was observed at the BER of 8.0×10^{-3} for the 10-Gbaud PAM4 signal when we set the optical feedback ratio to be -14 dB. The results also showed that it would be difficult to achieve the error-free transmission of this PAM4 signal if there is any bad connector having $>1.58\%$ reflection (i.e., -18 dB) even in the back-to-back condition. After the transmission over 2.4 km of SMF, the receiver sensitivity of this PAM4 signal was measured to be -12.9 dBm in the absence of the external optical feedback, as shown in Fig. 5(b). Thus, the power penalty caused by the fiber dispersion was estimated to be 1.5 dB for this 10-Gbaud PAM4 signal. We also noted that, due to the fiber dispersion, the BER curves measured after the transmission over 2.4 km of SMF became less steep compared to those curves in Fig. 5(a). As a result, the error floor caused by the external optical feedback (i.e., increased RIN) became higher after the SMF transmission. For example, when we set the optical feedback ratio to be -18 dB, an error floor was observed at the BER of $\sim 1.4 \times 10^{-3}$ after the transmission over 2.4 km of SMF. We expected that the power penalty of the PAM4 signal would also be unchanged with the baud rate as the OOK signal. However, the measured power penalty (@BER $= 2.4 \times 10^{-4}$) in the back-to-back condition was increased as we increased the baud rate from 5 to 14 Gbaud, as shown in Fig. 5(c). As described earlier, this was due to the limited bandwidth of the VCSEL. Thus, we could mitigate this problem by using electrical equalizers. For example, when we applied a 10-tap FFE, the power penalty of the 10-Gbaud PAM4 signal measured at the optical feedback ratio of -18 dB was reduced to 3.6 dB. However, when we increased the baud rate to 14 Gbaud, it was not possible to achieve the threshold BER of 2.4×10^{-4} even with the use of this FFE. We also noted that, regardless of the baud rate, the threshold BER could not be achieved if the optical feedback ratio was >-16 dB.

III. Summary

We evaluated the effects of the external optical feedback on the OOK and PAM4 signals operating at various baud rates in a short-haul SMF link implemented by using a commercial 10G-class 1.55-μm VCSEL. We intentionally set the bias current of this VCSEL to be as high as 12 mA to minimize the RIN and spectral broadening caused by the external optical feedback while maximizing its modulation bandwidth. It was of no use to increase the bias current to be higher than 12 mA for these objectives. In addition, the bias current should not exceed 12 mA for the generation of the equally spaced PAM4 signal having an ER of 8 dB. Under this bias condition, the 3-dB bandwidth of this VCSEL was measured to be 7.3 GHz. The results showed that, as expected, the PAM4 signal was much more sensitive to the external optical feedback than the OOK signal. For example, for the 10-Gbaud OOK signal, the power penalty was measured to be only 0.4 dB (@BER $= 5 \times 10^{-5}$) in the back-to-back condition even when we set the optical feedback ratio to be as large as -14 dB. We also observed that this power penalty was not degraded by the 2.4-km long SMF transmission. In comparison, for the 10-Gbaud PAM4 signal, an error floor was observed at the BER of $\sim 8.0 \times 10^{-3}$ even in the back-to-back condition when we set the optical feedback ratio to be -14 dB. In addition, the performance degradation was measured to be worsened after the transmission over 2.4 km of SMF (since an error floor was observed at the BER of $\sim 1.3 \times 10^{-2}$ under the same feedback ratio). The results also showed that, for both the OOK and PAM4 signals, the power penalties caused by the external optical feedback were measured to be about the same regardless of the baud rates except at the high baud rates (at which the performances were also limited by the insufficient bandwidth of the VCSEL used in this experiment). From these results, we concluded that it would not be possible to achieve the error-free transmission of the high-speed PAM4 signal in the VCSEL-based SMF link if there is any bad fiber connector having $>2.5\%$ reflection (even if there is no other source of the signal distortions such as the fiber dispersion and bandwidth limitation). It should also be noted that the effects of the optical feedback were measured to be much worse when we set the bias current to be lower than 12 mA for this VCSEL.

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