The Development of the 1060 nm 28 Gb/s VCSEL and the Characteristics of the Multi-mode Fiber Link

Tomofumi Kise[*1], *Toshihito Suzuki*[*2], *Masaki Funabashi*[*1], *Kazuya Nagashima*[*1], *Hideyuki Nasu*[*1]

ABSTRACT In recent years, the demand for the large capacity data transmission has been rapidly expanding in the data centers and the enterprise networks. For the purpose of short distance transmission such as the connection between racks, active optical cable (AOC) using a vertical cavity surface emitting laser (VCSEL) and multi-mode fiber (MMF) have been introduced. On the other hand, due to the increase in the size of data centers, more than 500 m transmission distance is required now, but in the case of conventional 850 nm VCSEL technology, the transmission distance is limited to about 100 m because of the effect of chromatic dispersion. We have been developing the VCSEL which operates at 28 Gb/s at the 1060 nm band where the high speed operation can be performed and the effect of chromatic dispersion is reduced. The optical link using the 1060 nm VCSEL mounted 4 channel parallel optical module and the 1060 nm optimized multi-mode fiber is constructed and the transmission characteristics were confirmed. Optical signals modulated by 28 Gb/s pseudo-random sequence 2^{31}-1 were transmitted. As a result, error free transmission was obtained even though the distance was 500 m. This technology is expected to be effective to support the optical transmission in the large scale data centers.

1. INTRODUCTION

In recent years, the adoption of optical interconnect as a technique to achieve high speed and parallel transmission has been rapidly progressing in the high-end routers, servers, super computers and other demanding applications. In the case of the transmission between racks with the distance of tens of meters, the replacement of the conventional copper cable with AOC has been progressing. AOC has superior bandwidth, transmission distance and also same electric interface as the older, copper cable. In these short distance applications (for example, a popular 10 Gigabit Ethernet) an 850 nm VCSEL is usually mounted as a light source to AOC. Standard MMF with the modal dispersion minimized at 850 nm is used. The current mainstream transmission speed per channel is 10 Gb/s (4 channels), but 25 Gb/s (4 channels) has been studied for next generation standard. On the other hand, it is thought that the optical interconnect of the next generation will be introduced to the transmission between the boards with transmission distance of several meters. In the inter-board transmission, the parallel optical module is densely implemented and also 25 Gb/s or higher speed operation is required. The 1060 nm VCSEL which we are developing has the advantage to realize the high-speed modulation operation due to the high differential gain and the low threshold current density compared to the 850 nm VCSEL [1)]. In addition, with the rapid spread and the large scale, the extension of distance from 300 m to more than 500 m is sought for the transmission distance required for inter-equipment connection. However, in the case of the conventional 850 nm VCSEL, the transmission distance is limited to about 100 m because of the effect of chromatic dispersion of fiber if the modulation speed is 25 Gb/s. While the chromatic dispersion of fiber is -90 ps (nm. km) at 850 nm, it is -34 ps (nm. km) at 1060 nm, only about one/third as high. Therefore, from the long distance transmission point of view, the 1060 nm VCSEL is very promising. The characteristics comparison of the 850 nm VCSEL and the 1060 nm VCSEL are summarized in Table 1. In addition to the transmission advantages, InGaAs material and fiber characteristics, a light of 1060 nm wavelength can be emitted from the back surface of substrate because the emitted light is transparent to GaAs substrate. Because of this, there is an added advantage where the degree of freedom of the package design is increased.

[*1] FITEL Product Division
[*2] Telecommunication & Energy Laboratories, R&D Division

Table 1 The Comparison of the 850 nm VCSEL and the 1060 nm VCSEL.

Item	InGaAs/GaAs based VCSEL (1060 nm)	GaAs/AlGaAs based VCSEL (850 nm)
Threshold voltage	1.17 V	1.46 V
Transparent current density	20 A / cm^2	100 A / cm^2
Differential gain: dg/dJ	40 x 10^{16} cm^2 / A	8 x 10^{16} cm^2 / A
Defect propagation velocity	From 0.01 to 0.1 µm / h (<110>)	From 2 to 10 µm / h (<100>)
Photodiode responsivity	0.75 A / W (InGaAs photodiode)	0.6 A / W (GaAs photodiode)
Multimode fiber loss	1 dB / km	2 dB / km
Fiber chromatic dispersion	-34 ps / (nm. km)	-90 ps / (nm. km)
Substrate transparency back-side emission	Yes	No
Eye-safety maximum optical output power (class 1)	+1.5 dBm	-2.2 dBm

In this report, the development of a 1060 nm VCSEL operating at 28 Gb/s and the experimental result of the transmission test using the 1060 nm optimized MMF link will be reported.

2. THE DEVELOPMENT OF THE 1060 nm 28 Gb/s VCSEL

2.1 The Structure of the Device and the Basic Characteristics

First, we will explain the 1060 nm VCSEL structure developed by Furukawa Electric. An InGaAs stained quantum well is employed as an active layer and there are features such as high differential gain, low threshold current density, slow propagation speed of dark line defect. Because of these features, high modulation speed, low power consumption and high reliability can be realized. Also because of longer wavelength, the operating voltage is reduced compared to 850 nm devices. It is expected to contribute to the lower power consumption. Figure 1 shows the device structure of the 1060 nm VCSEL. We employ the double intra cavity (DIC) structure. This structure is different from the conventional VCSEL and has the feature that a stable differential resistance is obtained because distributed bragg reflector (DBR) mirror having a plurality of semiconductor hetero barrier is not the current path. Also the DIC structure is possible to lower the optical loss because the DBR mirror layer can be non-doped.

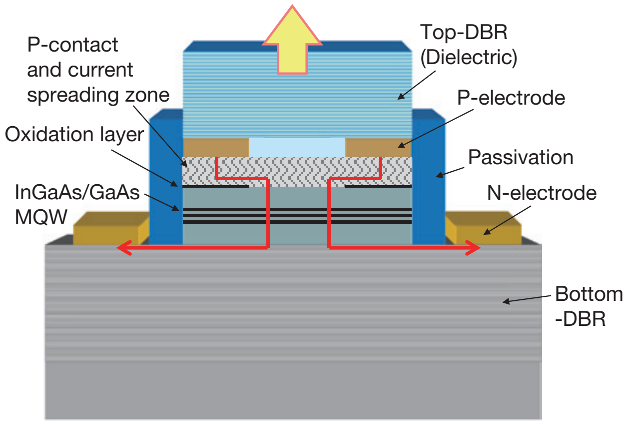


Figure 1 The device structure of the 1060 nm VCSEL.

In order to achieve a 25 Gb/s or faster operation, (A) improvement of relaxation oscillation frequency and (B) low capacitance are required. As a measure of (A), short cavity is effective to reduce the volume of the active layer. For this purpose, the layer thickness corresponding to the cavity is reduced and the optical confinement to active layer is improved. Also, to confine injected carrier to active layer effectively and to improve the differential gain, the detailed study about quantum well structure (number of wells, well thickness and the barrier thickness) and optimization was carried out. With regards to measure of (B), the capacitance reduction due to the oxidation layer is dominant factor in the parasitic capacitance of the VCSEL. The parasitic capacitance is reduced by thickening the oxidation layer, but on the other hand, the accumulation of strain by oxidation layer is increased and it could lead to the degradation of the reliability. In consideration of these trades off, the optimization of oxidation layer thickness was studied.

Figure 2 shows the LIV characteristics of VCSEL with an aperture diameter of 6 μm. The low threshold current of 0.45 mA is obtained. Also, it is the feature of the long wavelength VCSEL that the voltage is suppressed to less than 2 V at the usual operating current of 6 mA.

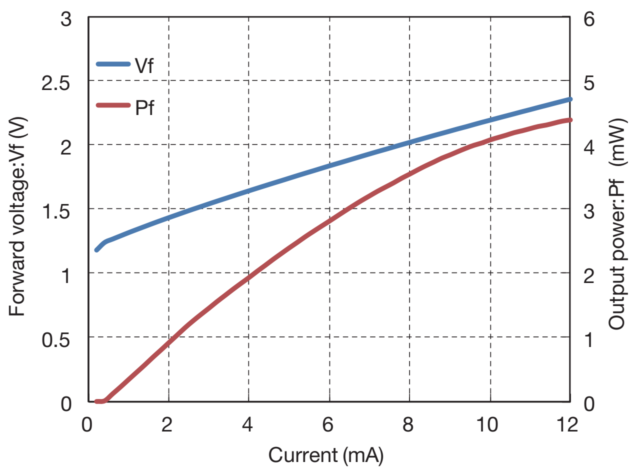


Figure 2 The LIV characteristics of the device with 6 μm aperture.

2.2 High Speed Modulation Characteristics

Then, the high speed modulation characteristics will be explained. Figure 3 shows the frequency response characteristics of the developed device at 25°C and 6 mA bias current. More than 20 GHz is obtained as 3 dB modulation bandwidth. The analysis of the frequency response characteristics by the combination of the optical response derived from the laser rate equations and the electrical response derived from the laser equivalent circuit (Figure 4) is carried out and the fitted result is shown in red line in the Figure 3. The experimental result can be explained well. From this analysis, 17 GHz was derived as a relaxation oscillation frequency and 70 ns^{-1} was derived as a damping factor γ. Figure 5 shows the plots of the relaxation oscillation frequency fr vs. normalized bias current. It can be seen that the high value of 10 GHz/ $(mA)^{1/2}$ is obtained for the parameter of D factor which is expressed by the gradient of the graph and indicates the modulation characteristics.

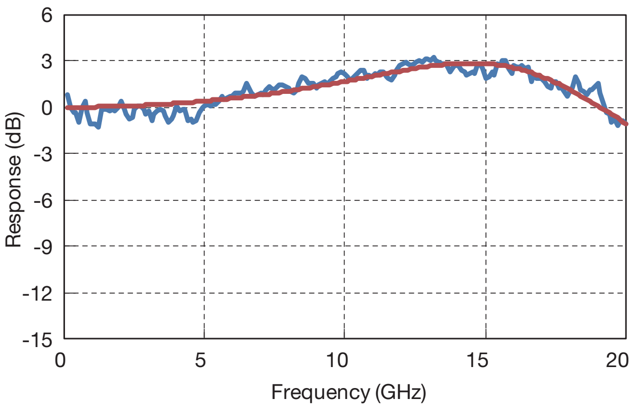


Figure 3 The frequency response of the device with γ = 70 ns^{-1}.

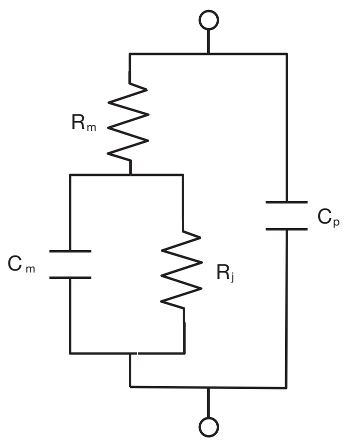


Figure 4 The equivalent circuit model of VCSEL.

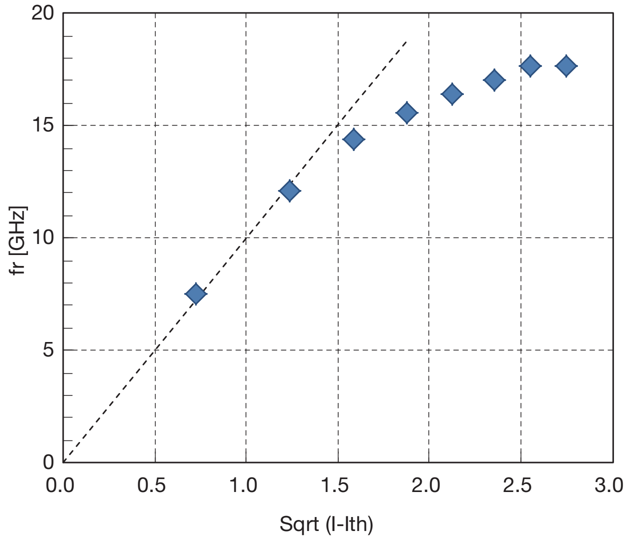


Figure 5 The relaxation oscillation frequency vs. normalized bias current.

On the other hand, the damping factor γ can be expressed as below from the rate equation of the laser.

$$\gamma = 4\pi^2 \tau_p f_r^2 + \gamma 0 \qquad (1)$$

Here, f_r represents the relaxation oscillation frequency and τ_p represents the photon lifetime. If the damping factor is small, it leads to overshoot in the eye diagram and the waveform degradation due to jitter and other factors. In order to increase the damping factor, it is necessary to prolong the photon lifetime τ_p, namely to reduce the optical loss of the resonator (the sum of the mirror loss and internal loss). In order to achieve these, the precise optimization of the doping profile and the adjustment of the reflectivity of upper DBR were performed. Because the DIC structure employed by us is non-doped mirror, it is essentially easy to obtain the low loss. Also the adjustment of upper DBR reflectivity can be performed easily by the additional deposition or etching of a dielectric DBR.

Figure 6 shows the frequency response characteristics of the device at γ = 100 ns^{-1}, 25°C and 6 mA bias current. 3 dB bandwidth is 18 GHz, but it can be seen that the flat frequency response characteristics is obtained even in the low frequency region.

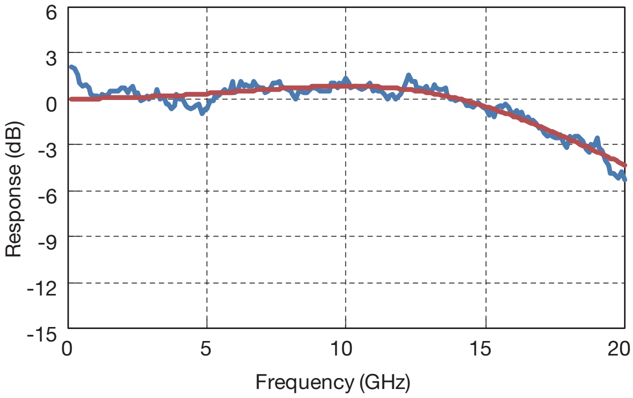


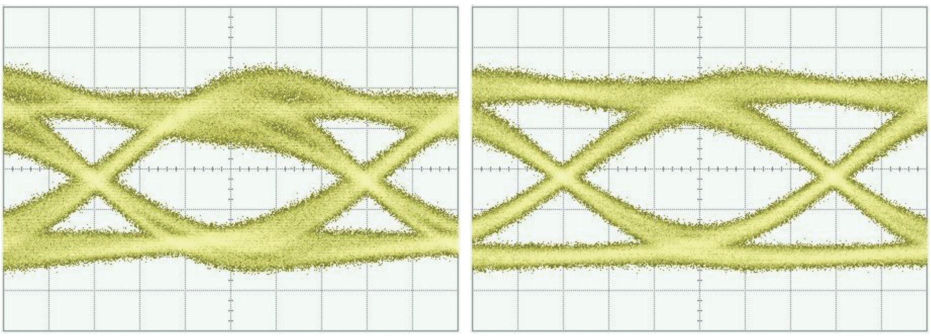
Figure 6 The frequency response of the device with γ =100 ns^{-1}.

The evaluation of the eye diagram for these developed VCSEL devices is performed using the signal of 28 Gb/s, NRZ, PRBS: 2^{31}-1. Figure 7 (a) is the eye diagram of the device with a damping factor γ of 60 ns^{-1} and Figure 7 (b) is the eye diagram of the device with 100 ns^{-1} at 28 Gb/s, respectively. In Figure 7 (a), the overshoot and jitter in the levels of 0 and 1 are remarkable. On the other hand, as you can see in the Figure 7 (b), it can be seen that a good eye opening is obtained by increasing the damping factor.

3. THE MULTI-MODE TRANSMISSION USING 1060 nm OPTIMIZED MMF

3.1 The Transmission Test using the 1060 nm Optimized MMF

Next, the transmission test was carried out using the 1060 nm VCSEL developed by Furukawa Electric and the 1060 nm optimized MMF with a core diameter of 50 μm developed by OFS. The reflective index profile of this MMF is adjusted to minimize the modal dispersion at the 1060 nm band. The set up for this transmission test is shown in Figure 8. The VCSEL is mounted on the 4 channel parallel optical transmitter module together with a driving IC and micro-optics (Picture in Figure 8) [2]. Optical receiver module in which a photo detector (PD) and a trans impedance amplifier (TIA) are integrated is also prepared as well and the transmission test was performed using both the transmitter and receiver modules. It should be noted that each optical module is driven and controlled in a dedicated evaluation board. Regarding the 1060 nm MMF used in this test, differential mode delay (DMD) which is presenting the modal dispersion was 0.12 ps/ m in the radial direction area of 0 to 23 μm. Also effective modal bandwidth is more than 4,000 MHz. km and the fiber corresponds to OM4 grade at 1060 nm.



(a) (b)

Figure 7 The eye diagrams at 28 Gb/s.
(a): γ =60 ns^{-1} (b): γ =100 ns^{-1}

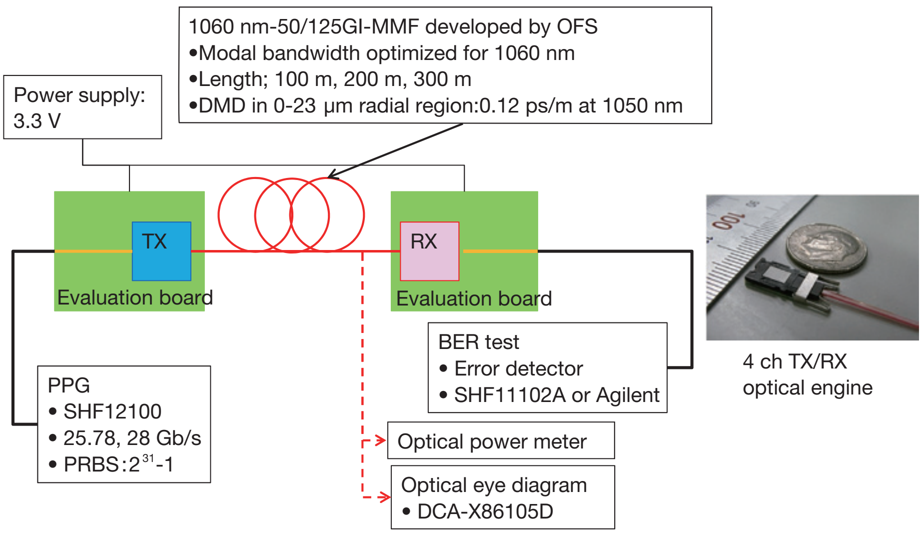


Figure 8 The experimental setup of the transmission test.

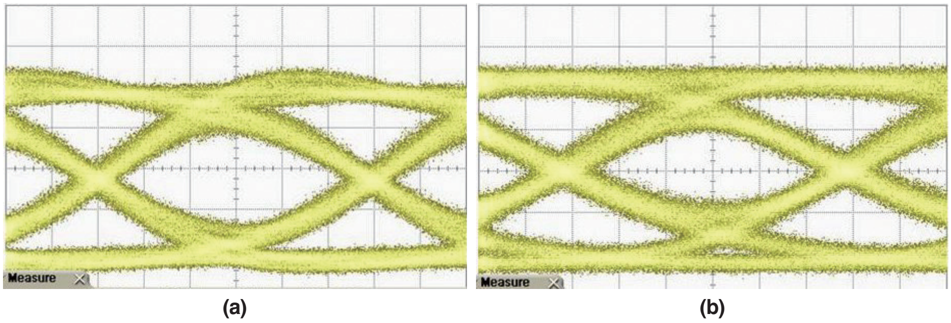


Figure 9 **The eye diagrams using the 1060 nm optimized MMF. (a): Back to back (b): After 500 m transmission**

Figure 9 (a) and (b) show the eye diagrams of back to back and after 500 m transmission, respectively. It can be seen that a good eye opening is maintained even after 500 m transmission. Figure 10 shows its BER characteristics. Error free transmission is confirmed at 100 m, 300 m and 500 m and the power penalty after 500 m transmission was 2.2 dB. Figure 11 shows the BER Bathtub curve. From this figure, the total jitter increases as the distance increases, but the total jitter after 500 m transmission is estimated to be 0.82UI in extrapolation by dual Dirac model and it is verified that jitter margin exists [3].

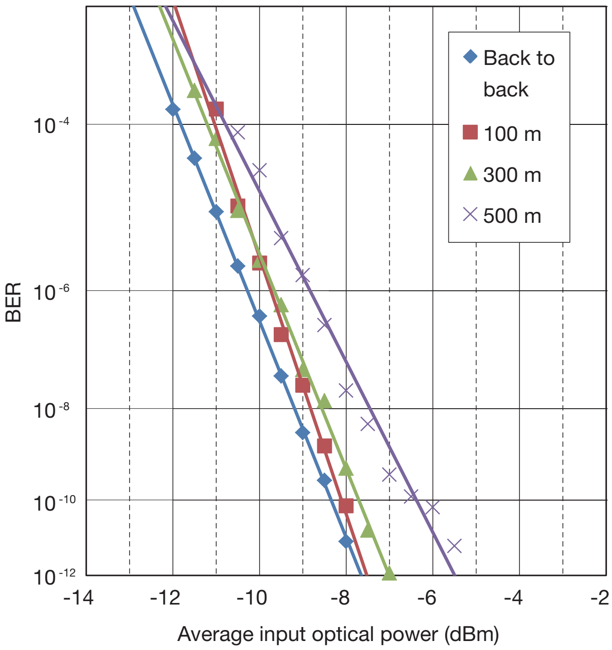


Figure 10 **The BER characteristics of transmission test using the 1060 nm optimized MMF at 28 Gb/s.**

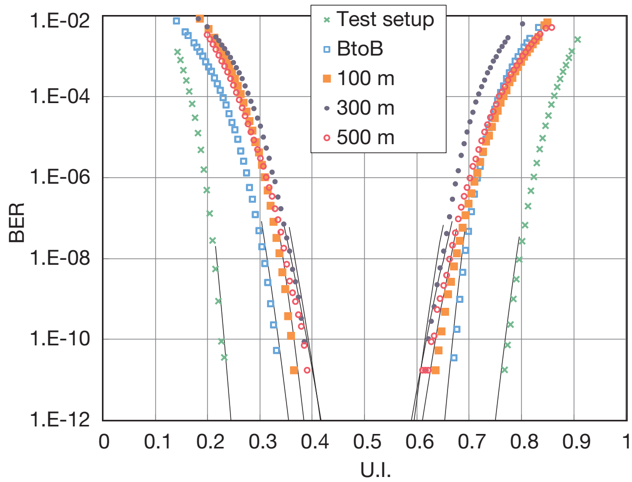


Figure 11 **The BER Bathtub curve of transmission test using the 1060 nm optimized MMF.**

3.2 The Transmission Test Using Modal Dispersion Compensated Link

At last, the new approach to the 1060 nm optimized MMF link carried jointly with Corning Inc. has been introduced [4]. Figure 12 shows the concept. MMF such as OM4 standardized for 850 nm has a DMD characteristic of right tilt due to the material dispersion as shown in Figure 12, on the left side of the chart. As a result, the effective modal bandwidth is significantly lowered. Therefore, in order to counteract this modal dispersion, the MMF link which the modal dispersion is minimized at the desired wavelength can be configured as a whole by combining with the MMF designed to have DMD characteristics of left tilt opposite to OM4. This is called modal dispersion compensated link. The DMD of 500 m modal dispersion compensated link was 0.09 ps/m in the core region of 0 to 23 μm and it is low enough for proper transmission. It is estimated that this link has the effective modal bandwidth of 10 GHz.km at the wavelength of 1060 nm.

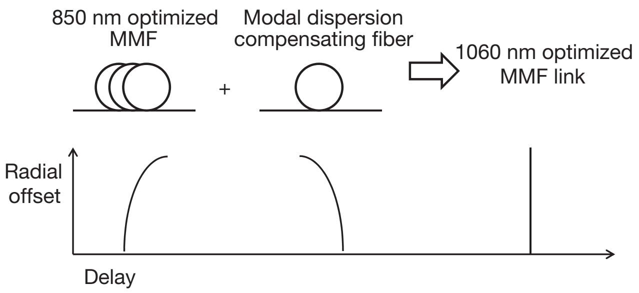


Figure 12 The concept of modal dispersion compensated link.

The BER characteristics of transmission test using this modal dispersion compensated link is shown in Figure 13. Error free transmission at 300 m and 500 m is realized and the power penalty is 1.2 dB and 2.3 dB, respectively.

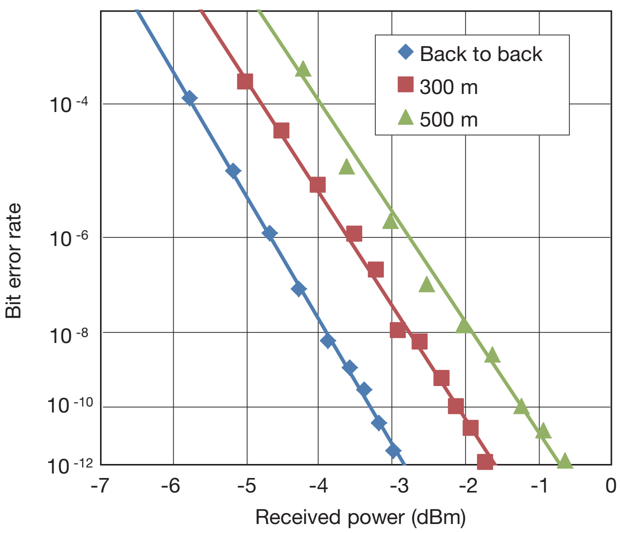


Figure 13 The BER characteristics of the modal dispersion compensated link at 25 Gb/s.

4. CONCLUSION

In this paper, we report the development of the 1060 nm VCSEL operating at 28 Gb/s. By improving the relaxation oscillation frequency, lowering the capacitance and optimizing the damping factor, the 3 dB modulation bandwidth of 18 GHz and the operation at 28 Gb/s are realized. Also, optical link was configured using developed 1060 nm VCSEL mounted 4 channel parallel optical module, the 1060 nm optimized MMF and the modal dispersion compensated MMF link, and error free transmission was confirmed. It is considered that this technology is promising to realize the high speed and the long distance transmission sought in the future data centers.

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