Low Power Consumption 10 Gbps×12 ch Parallel Optical Module for Optical Interconnection

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ABSTRACT Recently, with rapid increases in the data volume processed in data centers, great expectations are placed on the introduction of optical interconnects with a transmission speed of higher than 10 Gbps per channel. Whereas optical interconnects show superior performance in terms of long-distance transmission, high-data rate transmission and low power consumption, the advantage mentioned last is presently drawing special attention, as the consciousness for the environment is on the rise among IT equipment manufacturers. Furukawa Electric has been developing a compact 10 Gbps×12 ch parallel optical module that is applicable to both inter-equipment and intra-equipment communications in data centers, and by using low-power consumption ICs and our high-efficiency 1 μm-range VCSEL that allows low-bias current driving, we have recently achieved a low power consumption of 7 mW/Gbps. This paper presents the structure and characteristics of parallel optical modules.

1. INTRODUCTION

With the rapid spread of the Internet, the data volume processed by servers and storages in data centers is rapidly increasing. To improve the data processing volume, efforts are being made to raise the speed of individual devices. And on the other hand, the communication speed in CPU-to-memory and device-to-device is needed to be increased, thereby making it essential to upgrade the speed of interconnections.

Heretofore, despite its high transmission loss, electric interconnects have been used for its low cost and ease of handling in interconnections in data centers and the like, because the transmission distance needed is rather limited. Recently, however, the data volume to be processed increases year by year, making it necessary to improve the data capacity that can be processed by one interconnection. Accordingly, a data rate in excess of 10 Gbps is often required these days even in intra-device communications, and this leads to the argument over the limits of electric interconnects, accompanied by active studies on the introduction of optical interconnects.

Figure 1 shows the boundary between optical interconnection and electrical interconnection, using transmission distance and signal speed as parameter [1]. The boundary shown in solid line indicates that, when a data rate exceeding 10 Gbps is required, electrical interconnect is expected to achieve a transmission distance of several meters at most. On the other hand, optical wiring can achieve longer distance data transmission because it has a significantly smaller transmission loss compared with that of electrical wiring, and it is less susceptible to noise from exterior environments. Optical interconnects include the parallel optical link using SNAP12 [2] capable of 300 m transmission by 2.72 Gbps×12 ch, and the optical link standardized by IEEE 802.3ae 10 GBASE-SR (10 GbE) [3]. Hereafter, standardization of IEEE P802.3ba 40 Gbps and 100 Gbps Ethernet task force (100 GbE) is scheduled in 2010, holding promise for parallel optical links having a data rate higher than 10 Gbps×10 ch.

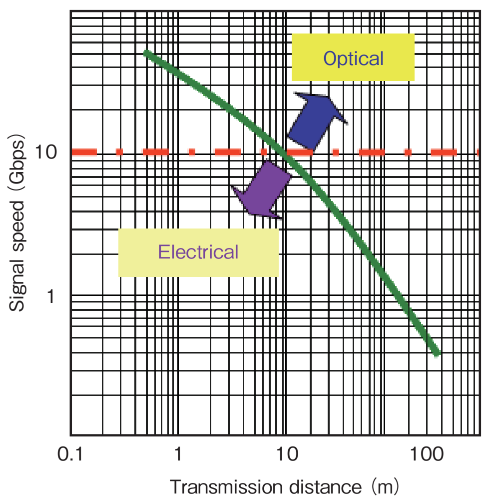

Figure 1 Boundary between optical interconnection and electrical interconnection, using transmission distance and signal speed as parameter.

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We have been developing a compact parallel optical module that can achieve a transmission capacity of 10 Gbps×12 ch for a distance of up to several hundred meters, being also applicable to high-density mounting, and a low-power consumption of 7 mW/Gbps has been achieved under the working conditions that match actual applications by using our high-efficiency 1 μm-range vertical cavity surface emitting laser (VCSEL) array [4), 5)]. This paper presents the concept, structure and characteristics of the developed module.

2. CONCEPT OF OPTICAL INTERCONNECTION MODULE

Optical interconnections can be classified, according to the transmission distance, into rack-to-rack, board-to-board, chip-to-chip and in-chip categories, and the transmission distance of these categories falls into longer than 10 m, around 1 m, around 10 cm and shorter than 10 cm, respectively. As the transmission distance decreases from the inter-rack to in-chip, components are required to be mounted in higher density along with higher downsizing. When it comes to optical module, parallel optical modules with a total data rate of several tens of Gbps are commercially available, representatives of which are those based on SNAP12 and active optical cable (AOC). Also, for board-to-board transmission, the development of a compact parallel optical module with a data rate of higher than 10 Gbps per channel has been reported [6), 7)].

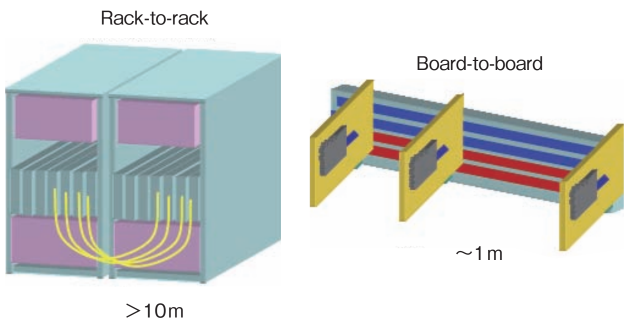

Figure 2 Schematic views of rack-to-rack and board-to-board interconnection.

As information processing capability increases in recent years, the power consumption in information processing facilities tends to increase, and this constitutes a pending problem. Also, the increase in power consumption due to the speed-ups of devices, together with the increase in the number of equipment, generates a concern. Furthermore, it is said that air-conditioners in the existing data centers consume more than 30% of the total electric power. This constitutes a major problem, together with the power consumption increases in air-conditioners to suppress temperature rises due to heat generation, and the one that is consumed to compensate for the decreased cooling efficiency caused by high-density arrangement of equipment. Introduction of optical technology into interconnects is expected to reduce transmission losses, and to improve the cooling efficiency in equipment because it can reduce the total amount of wiring thereby increasing the space for free air convection. However, since speed-up of information processing performance is ever accelerating presently, reduction of transmission loss and improvement of cooling efficiency alone can not suppress the increases in power consumption.

Figure 3 shows the trends in the power consumption per 1 Gbps required for interconnections by 2020. As can be seen, the power consumption is around 40 mW/Gbps presently because electric interconnects constitute the mainstream, but it is expected to reduce to 10 mW/Gbps in 2012 due to employment of optical interconnects for board-to-board transmission, then to 3 mW/Gbps in 2016 due to use of optical interconnects for chip-to-chip transmission, and finally to 1 mW/Gbps in 2020 due to use of optical interconnects for in-chip transmission, thus showing a remarkable reduction in power consumption.

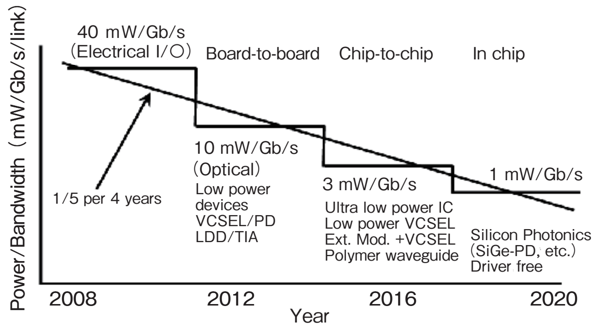

Figure 3 Trends in power consumption of interconnections [1), 8)].

We have been developing a compact parallel optical module with a data rate of 10 Gbps×12 ch, a power consumption of less than 10 mW/Gbps, that is applicable to both rack-to-rack and board-to-board applications. To satisfy both a data rate of 120 Gbps and low power consumption, laser diode driver (LDD) and trans-impedance amplifier (TIA) utilizing bipolar complimentary metal-oxide-semiconductor (BiCMOS) technology are employed. In addition, a 1 μm-range indium-gallium-arsenide (InGaAs) VCSEL array is used for the transmitting module, and an InGaAs photo diode (PD) array having high responsivity at the 1 μm-range for the receiving module.

Compared to 850 nm-range gallium-arsenide (GaAs) VCSEL that is generally used for optical interconnections, the 1 μm-range VCSEL has higher differential gain [9)], and a higher relaxation oscillation frequency is available using the same threshold and drive currents, so high-speed operation becomes possible [10)]. Because sufficient bandwidth is obtained with a lower drive current at the data rate of 10 Gbps, it becomes possible to decrease power consumption of optical modules.

In terms of transmission characteristics of optical links, it becomes necessary to assure large power budget margin for transmission between the optical transmitting module (TX) and receiving module (RX). Table 1 compares the characteristic items determining the power budget margin for transmission in the 1 μm-range and 850 nm-range.

Table 1 Comparison of the characteristics of optical link components at 1050 nm and 850 nm.

Items	Details	1 μm-range (1050 nm)	850 nm-range (850 nm)
Rx-module, PD	Responsivity	0.75 A/W	0.6 A/W
Optical fiber	Transmission loss	0.95 dB/km	2.09 dB/km
	Chromatic dispersion	−34.01 ps/(nm·km)	−90.42 ps/(nm·km)
Tx-module, Eye safety	Maximum optical output power	+1.5 dBm Class 1, 12 ch module	−2.2 dBm Class 1, 12 ch module

The InGaAs PD we use for the RX has a responsivity of 0.75 A/W at 1050 nm, which is larger than that of commonly used GaAs PD, i.e., 0.6 A/W. Given the fact that the optical responsivity of RX is an important parameter constituting an optical link, the use of the 1 μm-range achieves better optical responsivity by about 1 dB.

Silica-based multi-mode fiber (MMF) has wavelength dependence in its transmission loss and chromatic dispersion. The transmission loss of the MMF used in this development at the 1 μm-range is lower than that at the 850 nm-range by about 1 dB/km. Since the chromatic dispersion at the 1 μm-range is about one third of that of 850 nm-range, when comparison is made based on the same wavelength width, signal waveform distortion can be suppressed low even at longer transmission distances. When a transmission distance exceeding several hundred meters is needed, use of the 1 μm-range that is less sensitive to chromatic dispersion is more effective.

The maximum optical output of a TX is specified by the IEC under the eye safety regulations [11]. In the case of 12-channel module using optical connection like MT connector, it is estimated that an optical output power that is larger by about 3 dB is available at the 1 μm-range in Class 1 specification. If the optical output of a TX can be set high, it becomes possible to obtain higher power budget margin.

From the comparisons above, it can be said that the 1 μm-range is more effective in designing an optical link that offers a large power budget margin in terms of transmission distance.

3. STRUCTURE OF THE DEVELOPED OPTICAL MODULE

Following the description in the preceding Section of some of the important concepts of parallel optical modules, the structure of the developed device will be presented in this Section. Figure 4 shows a photo of the optical module of pig-tail type. The mechanical size excluding the pig-tail are 13×13×3.4 mm^3, sufficiently compact for high-density mounting, and an electrical interface adapted to the 11 mm^2 footprint is provided on its bottom. The heat generated by the IC (LDD or TIA) is conducted to a heat sink to be dissipated via a metal cover provided atop.

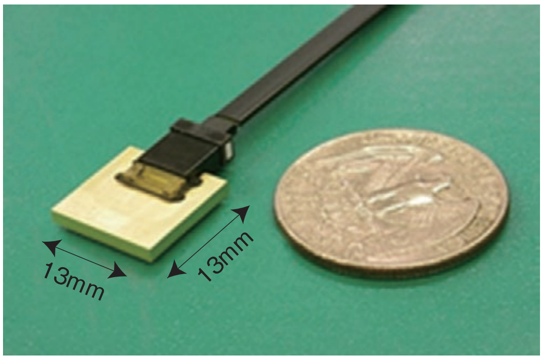

Figure 4 Photo of parallel optical module [12].

When the optical module is mounted on a PCB, which is a possible configuration envisioned in board-to-board transmission, many other devices are also mounted on the same PCB. If the optical module is directly mounted using solder, it would be necessary to replace the whole PCB in case of malfunction. We have developed, therefore, a pluggable socket as electrical interface [13] in order to make module replacement easy. Figure 5 shows an example of optical module mounted by using an electrical pluggable socket. The pluggable socket has a set of spring pins two-dimensionally arrayed at 1 mm pitch, and the high-speed I/O pin configuration has a wide-bandwidth of more than 10 GHz. The heat sink is used to press the optical module against the socket, thereby electrically connecting the module and the PCB to effect signal transmission.

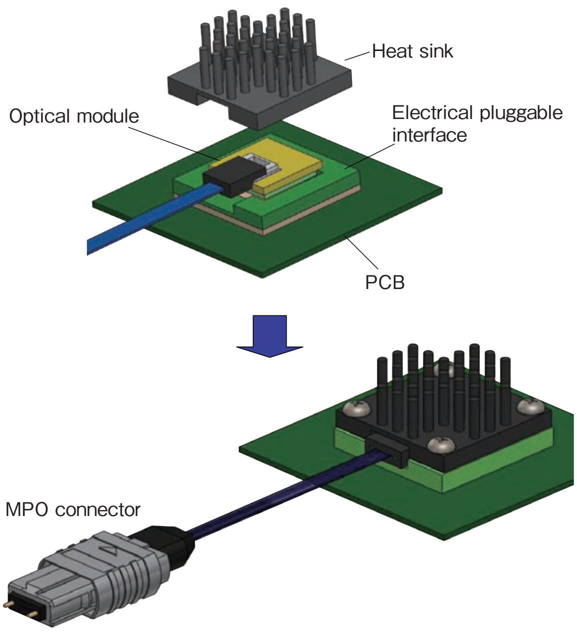

Figure 5 Parallel optical module and electrical pluggable socket.

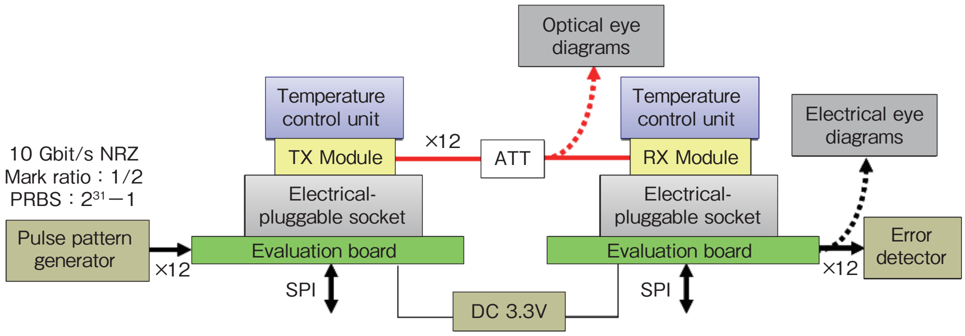

Figure 6 Block diagram of test setup for optical module [14].

4. CHARACTERISTICS OF OPTICAL MODULE

Characteristics of the optical module will be presented in this Section. Figure 6 shows the evaluation system for the optical module. The TX and RX optical modules are each mounted onto the evaluation board via the electrical pluggable socket; a set of 12-channel broadband differential transmission lines is provided on the board; they are connected with a pulse pattern generator (PPG), oscilloscope and error detector, via RF cables equipped with compact, broadband connectors; and a temperature control unit is used to control the case temperature of the optical module. While changing the case temperature, measurements were made of the optical output of TX, the electrical output waveform of RX in back-to-back (BTB) transmission and the bit-error-rate (BER).

Figure 7 shows the output waveforms of the TX and RX under 12-channel simultaneous operation at different temperatures from 15℃ to 80℃. The bias current of the VCSEL in TX was set to 4 mA, while the extinction ratio was 4.5 dB at 25℃. It can be seen that although the temperature rise from 15℃ to 80℃ increases the waveform overshoot, good eye opening is obtained. With the RX also, good performance was obtained including a differential amplitude of 240 mVpp, rise time/fall time of 35.7 ps/37.5 ps and good eye opening at the full temperature range.

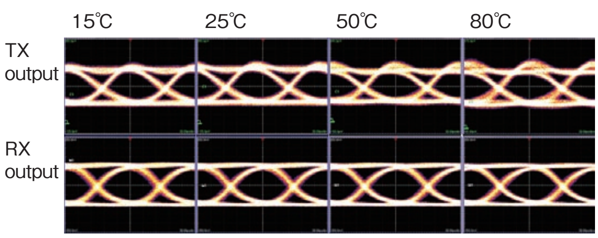

Figure 7 Output waveforms of TX-module and RX-module [14].

Figure 8 shows the BER characteristics in back-to-back transmission. The minimum optical sensitivity at BER=10^{-12} is seen to change from –11 dBm to –9.5 dBm at different temperatures from 15℃ to 80℃. Given an optical output of TX of –4 dBm, the power budget margin of the optical link is 5.5 dB. Transmission penalty can be suppressed by optimizing the optical output of TX, transmission distance and optical-fiber bandwidth, but in general, it is necessary to make an allowance of about 3 dB. Thus in this study, the optical link has achieved a margin higher than 2 dB.

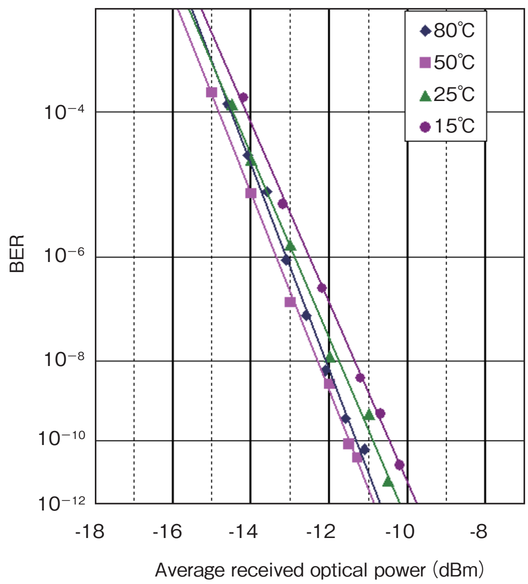

Figure 8 BER characteristics at temperatures from 15°C to 80°C [14].

Figure 9 shows the relationship between the bias current of the VCSEL in TX and the power consumption at 25℃ and 80℃. It can be seen that the power consumption of TX is proportional to the bias current, and the proportionality coefficient is larger for the case temperature of 80℃.

The optical output waveform of selected 850 nm VCSELs was evaluated at 25℃, and the results suggested that higher than 5 mW/Gbps was expected for TX power consumption because good eye-opening was obtained at a bias-current higher than 6 mA. In the case of the TX that mounted 1 μm-range VCSEL, good optical-output waveform and error-free transmission with BER=10^{-12} in BTB were obtained at a bias-current of 4 mA. The TX power consumption under this condition is about 3 mW/Gbps, which is about 60% that of the TX employing a conventional 850 nm VCSEL.

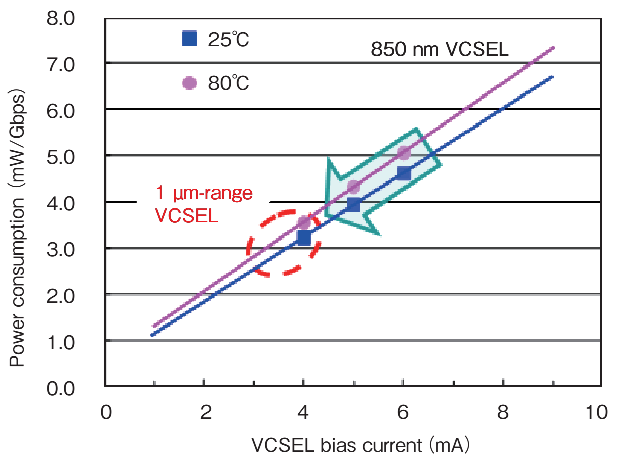

Figure 9 Bias-current dependency of TX-module power consumption [14].

Figure 10 shows the relationship between the total power consumption of TX plus RX and temperature from 15℃ to 80℃, indicating that the power consumption per 1 Gbps is 7 mW/Gbps. In extending transmission distances, the power consumption of TX may rise due to possible increase of the extinction ratio of TX in consideration of transmission penalty. However, in view of the fact that it has a sufficient margin up to 10 mW/Gbps, it can be said that this optical module adequately satisfy the power consumption estimated for 2012.

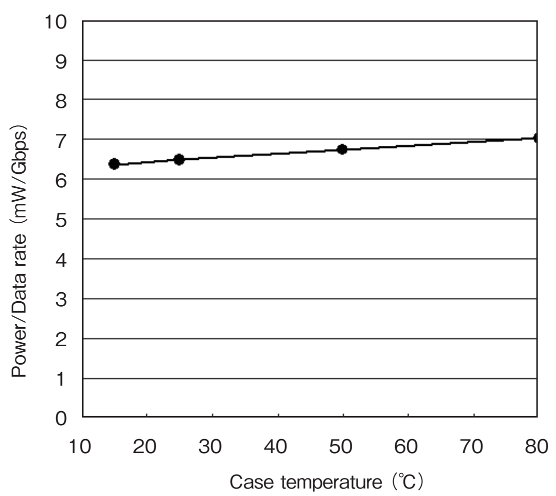

Figure 10 Case-temperature dependency of TX-module power consumption [14].

5. TRANSMISSION CHARACTERISTICS OF 1 μm-range OPTICAL LINK

Following the description of low-power operation of the 1 μm-range optical link in Section 4, this Section will present the transmission characteristics of optical links using several kinds of optical fibers.

5.1 Upper Limit of Transmission Distance of 1 μm-range Optical Link

Whereas the transmission distance in the rack-to-rack transmission at 10 Gbps/ch is said to be 300 m at most, it is sometimes required to lengthen it to 300 m or longer. The transmission distance is strongly affected by the mode dispersion of MMF, and the effect is expressed by the fiber bandwidth, so that MMFs for optical interconnects are standardized by an international regulation for their bandwidth. The International Electrotechnical Commission (ISO/IEC) 11801 defines the fiber with the minimum bandwidth higher than 500 MHz·km at 850 nm/1300 nm as OM2, and the one with an effective minimum bandwidth higher than 2000 MHz·km at 850 nm as OM3. The 10GbE specifies OM2 for transmission up to 82 m, and OM3 for up to 300 m, and for transmission beyond 300 m, standardization of OM4 fiber with an effective minimum bandwidth of 4700 MHz·km is under study.

We prototyped an MMF whose bandwidth was optimized for 1050 nm in wavelength to construct a 1 μm-range optical link, and investigated the upper limit of transmission distance of the optical link. The over-filled launched (OFL) bandwidth of the fiber was 4300 MHz·km, sufficiently wideband characteristics almost equivalent to the effective bandwidth of OM4.

Figure 11 shows optical output waveforms after transmission over different distances. Although almost no waveform degradation is seen from BTB up to 650 m, the inter-symbol interference (ISI) penalty begins to increase from 800 m resulting in deterioration of eye opening. Between the BTB and 1000 m, the extinction ratio deteriorates by nearly 2 dB, and at 1300 m the waveform deterioration reaches such a level that the rise time/fall time can not be measured.

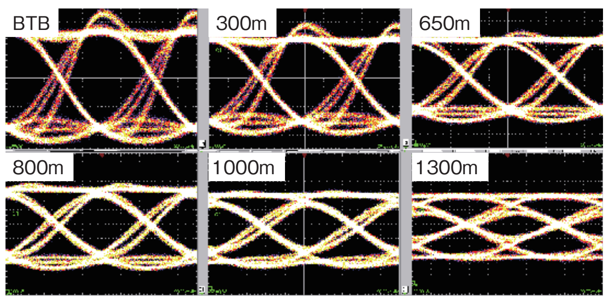

Figure 11 Optical eye diagram after transmission over different distances.

Figure 12 shows the BER characteristics of the optical link. Although an error floor is seen in the 1300 m transmission due to an S/N degradation due to ISI penalty, error-free transmission is achieved up to 1000 m with BER=10^{-12}, demonstrating an optical sensitivity lower than –8 dBm. Given the fact that the upper transmission limit of this optical link is defined to be more than 1000 m, it has been demonstrated that the 1 μm-range optical link is appropriate to applications up to 1 km.

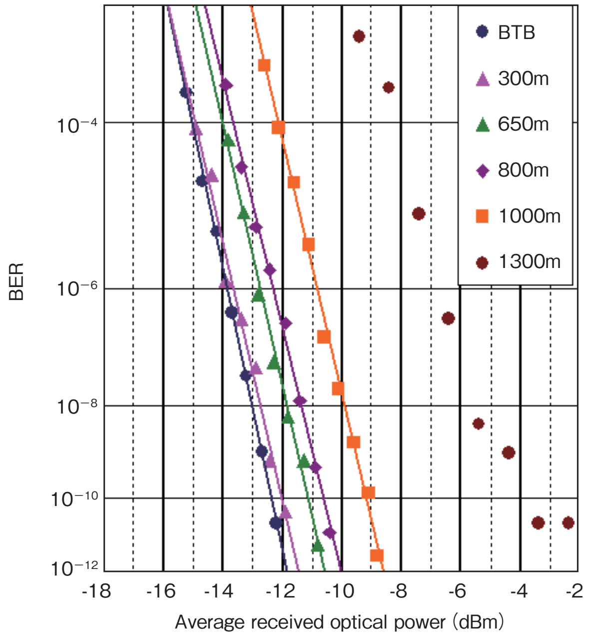

Figure 12 **BER characteristics after transmission over different distances.**

Figure 13 shows the relationship between transmission distance and power penalty, which is defined as optical sensitivity difference using BTB as a benchmark. The dots indicate the actual measured data obtained from the BER measurements mentioned before, while the solid lines correspond to the evaluation results calculated using the spread sheet disclosed by IEEE [15], obtained under the conditions of the center wavelength of 1050 nm, root mean square (rms) wavelength width of 0.42 nm and the OFL bandwidth of MMF of 4300 MHz·km. Power penalties at 700 m and 1000 m in the estimation are 3 dB and more than 9 dB, respectively, but the data show a power penalty of 3.2 dB at 1000 m, which is significantly lower than estimation. This may be attributed to the fact that the propagation condition within the MMF in the optical link differs from OFL conditions, and the propagation modes are limited resulting in an actual bandwidth that is larger than the OFL condition. The dashed line shows the calculated results of the power penalty, when the center wavelength is set to 850 nm while other conditions are made the same. Transmission distance at a power penalty of 3 dB is expected to be less than 500 m. On the other hand, the transmission distance at 1050 nm in wavelength is estimated to be 700 m, longer than the distance at 850 nm by 200 m, because the 1050 nm chromatic dispersion is smaller than that at 850 nm. Therefore, in the case of transmission longer than 500 m employing a wide-bandwidth MMF, a larger power budget margin is expected than 850 nm, by using the 1 μm-range wavelength.

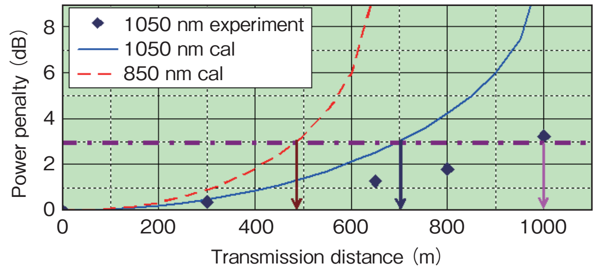

Figure 13 **Relationship between power penalty and transmission distance.**

5.2 Transmission Characteristics of 1 μm-range Optical Link Using Conventional MMF

Although silica-based MMFs used in optical interconnections are classified into OM2 and OM3 in terms of transmission bandwidth, these are targeted at usage in 850 nm and 1300 nm. Since the 1 μm-range bandwidth for OM2 and OM3 is not standardized, their performance is not widely known. The transmission characteristics of 1 μm-range optical links using OM2 and OM3 will be presented here.

In the transmission shorter than 300 m using silica-based MMFs, the effects of chromatic dispersion is small while the bandwidth limits due to mode dispersion is dominant, so that the bandwidth of the MMF at the wavelength in use becomes important. Table 2 shows the bandwidth of the OM2 and OM3 used in this study. The 1060 nm OFL bandwidth of OM2 is 2262 MHz·km, larger than those at 850 nm and 1300 nm, and according to the estimation using the IEEE spread sheet, the fiber has a 3 dB penalty distance of 350 m promising a possible transmission distance longer than 300 m. On the other hand, although OM3 has a bandwidth of 1094 MHz·km, smaller than the 850 nm OFL bandwidth due to the fact that the fiber is optimized for 850 nm, the fiber is estimated to have a transmission distance longer than 150 m.

Table 2 **OFL bandwidth of OM2 and OM3 used.**

Category	850 nm/1300 nm OFL Bandwidth	1060 nm OFL Bandwidth
OM2	850 nm, 789.9 MHz·km 1300 nm, 1602.4 MHz·km	2262 MHz·km
OM3	850 nm, 4509 MHz·km 1300 nm, 708 MHz·km	1094 MHz·km

Figures 14 and 15 show the BER characteristics of 1 μm-range optical links using OM2 and OM3. Both OM2 and OM3 have been confirmed to provide error-free transmission with BER=10^{-12}, from BTB to 300 m. The power penalty of the OM2 at 300 m transmission is less than 2 dB, demonstrating some power budget margin for 300 m transmission. Since OM3 increases in transmission power penalty by more than 2 dB, from 150 m to 300 m, the transmission limit is estimated to be around 300 m. But up to 150 m, it can be seen that the fiber has some power budget margin. Thus it has been demonstrated that the 1 μm-range optical links using OM2 and OM3 are fully capable of transmission up to 150 m, and that the optical link using OM2 is applicable to up to 300 m.

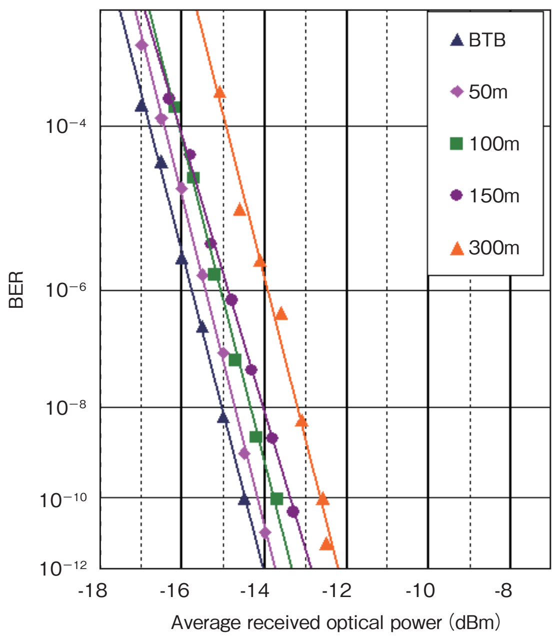

Figure 14 BER characteristics after OM2-MMF transmission.

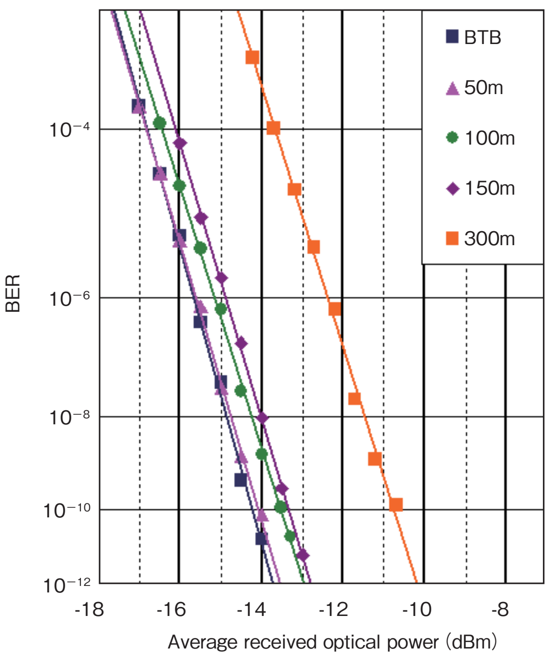

Figure 15 BER characteristics after OM3-MMF transmission.

6. CONCLUSIONS

We have developed a compact 10 Gbps×12 ch parallel optical module capable of high-density mounting, targeted at board-to-board optical interconnects. By using the 1 μm-range VCSEL array, PD array and low-power consumption ICs based on the BiCMOS technology, a low power consumption of 7 mW/Gbps has been achieved in paired TX-RX 12-channel simultaneous transmission. The 1 km transmission using an MMF optimized in the 1 μm-range has been achieved, together with the 300 m transmission using the OM2 and OM3 fibers demonstrating that the 1 μm-range optical link is appropriate to extensive applications. In view of the current trend toward lower power consumption, we intend to promote product development in response to the increasing needs for optical interconnects, taking advantage of the features of 1 μm-range including low power consumption.

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