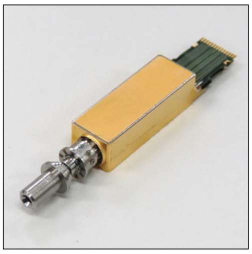

# 4-ch Integrated Optical Receiver Module with Semiconductor Optical Amplifier for Over 100-Gbit/s and 40 km Transmission

Kyohei MAEKAWA*, Kazuaki MII, Toru HIRAYAMA, Ryota TERANISHI, and Hiroshi HARA

To address the needs for increasing data traffic resulting from the widespread use of advanced mobile terminals and the diversification of internet-based services, over 100-Gbit/s optical transceivers have been used in optical communication systems of data centers. Furthermore, there has been a strong demand for extended reach connection between data centers. We have developed a new compact receiver with a semiconductor optical amplifier for 40 km/80 km transmission. This paper describes the design and typical characteristics of the new optical receiver.

Keywords: 100GBASE-ER4, semiconductor optical amplifier (SOA), variable optical attenuator (VOA), optical receiver module, QSFP28

## 1. Introduction

In recent years, along with the widespread use of smartphones and other sophisticated communication terminal devices, users have become able to easily enjoy various content on the internet. In addition, user's expectations are high for the Internet of Things (IoT) owing to the utilization of big data and the commercialization of 5G. In these circumstances, data traffic has sharply increased, and there is strong demand for improved communication speed and miniaturized communication devices.

Data centers are principal network facilities in which optical communication devices operating at higher than 100 Gbit/s have been introduced. A key component of these devices is the optical transceiver. Small optical transceiver products including the QSFP28 and QSFP-DD*[1] are in wide use. Meanwhile, for long-haul transmission, as is required by networks between data centers, semiconductor optical amplifier (SOA) modules are used to compensate for losses. A challenge with SOA modules has been that it is difficult to mount them together with an optical receiver module on a small optical transceiver.

The Transmission Devices Laboratories of Sumitomo Electric Industries, Ltd. and Sumitomo Electric Device Innovations, Inc. developed four-channel (4-ch) integrated optical receiver modules[(1)–(4)] and SOA modules[(5)] that can be mounted on small optical transceivers for over 100 Gbit/s applications. By mounting an SOA on an optical receiver module based on these designs, the two companies have developed a 4-ch integrated optical receiver module capable of long-haul transmission for 40 km at a rate over 100 Gbit/s in a compact body.

## 2. Target Specifications

Table 1 shows target specifications, which used 100GBASE-ER4 established in IEEE 802.3ba supporting 40 km reach for reference. Optical communication uses wavelength division multiplexing (WDM) as a technique of raising transmission capacity to simultaneously transmit multiple wavelengths of light through a single optical fiber. The four wavelengths of the LAN-WDM*[2] grid in the 1300 nm band are used in 100GBASE-ER4.

The modulation scheme is non-return-to-zero (NRZ) at a transmission rate of 25.78125 Gbit/s per wavelength, with the sum of the four wavelengths being 103.125 Gbit/s.

Table 1. Target Specifications for Optical Receiver Module

| Parameter | | Specification | Unit |
|---|---|---|---|
| Data rate | | 25.78125 ± 100 ppm | Gbit/s |
| Modulation scheme | | NRZ | - |
| Wavelength | Lane 0 | 1294.53 ~ 1296.59 | nm |
| | Lane 1 | 1299.02 ~ 1301.09 | |
| | Lane 2 | 1303.54 ~ 1305.63 | |
| | Lane 3 | 1308.09 ~ 1310.19 | |
| Receiver sensitivity (OMA*[3])† | | ≤ -21.4 | dBm |
| Overload (OMA)† | | ≥ -4.5 | |

† Optical power at: Bit error rate = $1 \times 10^{-12}$

## 3. Configuration of 4-ch Integrated Optical Receiver Module

Photo 1 shows the exterior of the 4-ch integrated optical receiver module. The package size is 22.6 mm × 6.7 mm × 5.3 mm, which can be mounted in the small optical transceiver QSFP28.

The 4-ch integrated optical receiver module is configured as illustrated in Fig. 1. It consists of a receptacle connected to an optical fiber, chip components such as an SOA, a variable optical attenuator (VOA), photodiodes (PDs), and a transimpedance amplifier (TIA), as well as an optical de-multiplexer and other optical components, a Peltier module,*[4] and a package. Figure 2 outlines the optical system of the 4-ch integrated optical receiver module. An optical signal entering the receptacle is attenuated by the

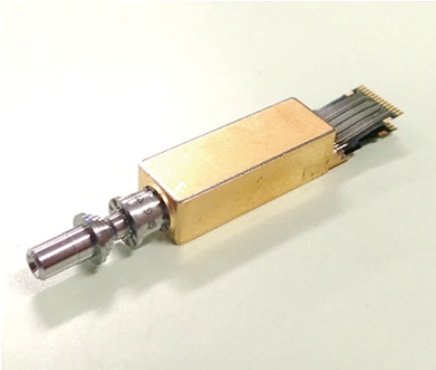

Photo 1. 4-ch integrated optical receiver module

VOA if it is a high-power signal, or is amplified by the SOA if it is a low-power signal. The light emitted from the SOA is repeatedly reflected in the optical de-multiplexer, divided by filters into different wavelengths, and coupled with the PD in each lane. The PDs are back-illuminated. A monolithic lens formed on the back enlarges the PD's active area diameter for a wider alignment tolerance. The optical signals are converted into electrical currents by the PDs, then converted into voltage signals and amplified by the TIA, and transmitted as differential electrical signals to the optical transceiver via the package and flexible printed circuits (FPCs). Moreover, to ensure that the SOA chip is driven within a specific operating temperature range, temperature control is performed according to the resistance feedback signal of a thermistor mounted near the SOA chip. The SOA chip is mounted together with the VOA and input/output lenses on a Peltier module. The VOA is a MEMS*5 chip, which attenuates the incident light to the SOA by operating a shutter blocking the light.

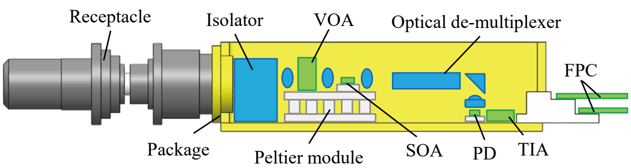


Fig. 1. Configuration of 4-ch integrated optical receiver module

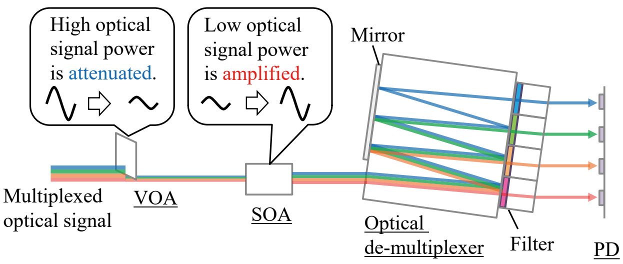


Fig. 2. Schematic diagram of optical system of 4-ch integrated optical receiver module

## 4. Characteristics of Optical Receiver Module

### 4-1 Optical characteristics

Figure 3 presents the responsivity spectrum of the 4-ch integrated optical receiver module. This module incorporates an optical de-multiplexer compatible with the LAN-WDM wavelength grid. In the figure, the dashed lines represent wavelength specifications. The module exhibited fluctuations of responsivity are controlled below 0.5 dB within the wavelength specification for each lane. Its isolation characteristics between lanes were favorable at 25 dB or more.

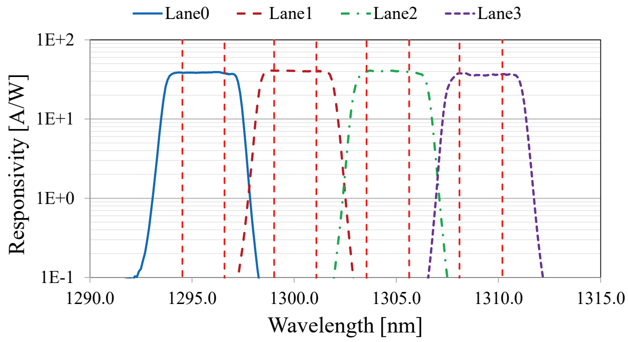


Fig. 3. Responsivity spectrum

Figure 4 plots the relationships between the SOA current and responsivity of the 4-ch integrated optical receiver module. The responsivity values take coupling loss, SOA gain, and PD responsivity into account.

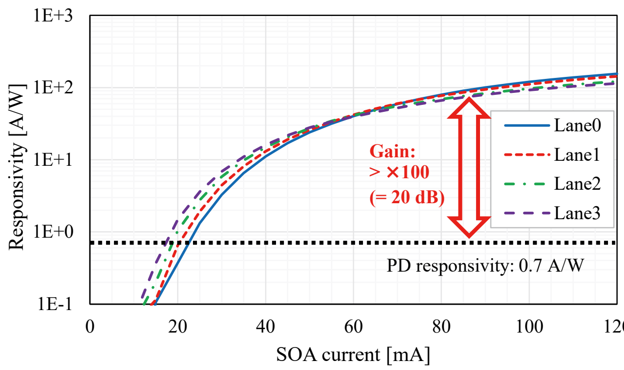


Fig. 4. SOA current dependence of responsivity

As the current flowing through the SOA increases, the gain increases; hence the responsivity increases. Owing to a low-loss optical system, the gain value was high at 100 (20 dB) or more in comparison with the responsivity of a discrete PD of approximately 0.7 A/W at an SOA current of 90 mA or more.

### 4-2 Receiver sensitivity characteristics

Figure 5 shows bit error rates observed when the receiver module case temperature was 25°C and the SOA was driven by a current of 80 mA at a temperature of 30°C, inputting a PRBS31*6 NRZ signal at a transmission rate of 25.78125 Gbit/s. The receiver sensitivity (OMA) at a bit error rate of $1 \times 10^{-12}$ was −25.9 dBm or less, producing a margin of 4.5 dB or more with respect to the target specification of −21.4 dBm. Although this result was produced when there was no difference in power between lanes, degradation in receiver sensitivity due to crosstalk was 0.5 dB or less even when power input to the other lanes was 4.5 dB higher than that input to the measured lane.

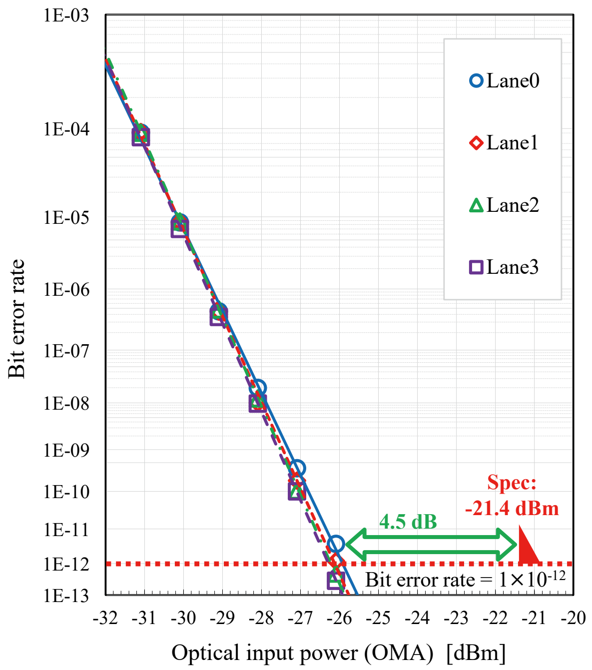


Fig. 5. Bit error rates at receiver sensitivity end

### 4-3 Overload characteristics

Figure 6 plots the attenuation characteristics of the VOA at a receiver module case temperature of 25°C and input power of 0 dBm. The VOA exhibited high attenuation of more than 20 dB at a low voltage of 3 V or less.

Figure 7 plots bit error rates observed at the overload end, with the SOA current being reduced to 30 mA. Other measurement conditions were the same as those used for the measurement of the receiver sensitivity. With no VOA mounted, all lanes exhibited an overload (OMA) of 0 dBm or more at a bit error rate of $1 \times 10^{-12}$, which failed to meet the specification. Therefore, it was necessary to mount the VOA to attenuate the input power. By utilizing the VOA in a suitable manner, the bit error rate for each lane was $1 \times 10^{-12}$ or less even at an input power of +6.9 dBm, or 2.4 dB higher than the target specification of +4.5 dBm. Thus, the results sufficiently met the specification for overload.

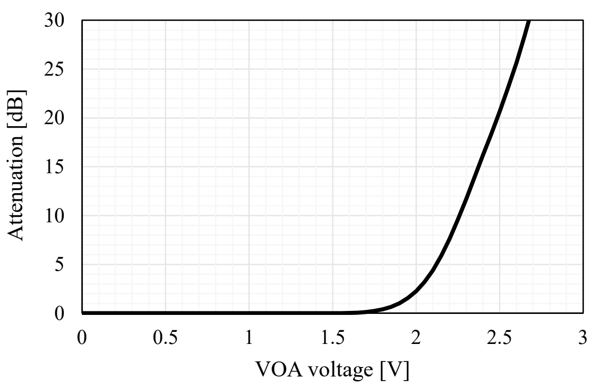


Fig. 6. Attenuation characteristics

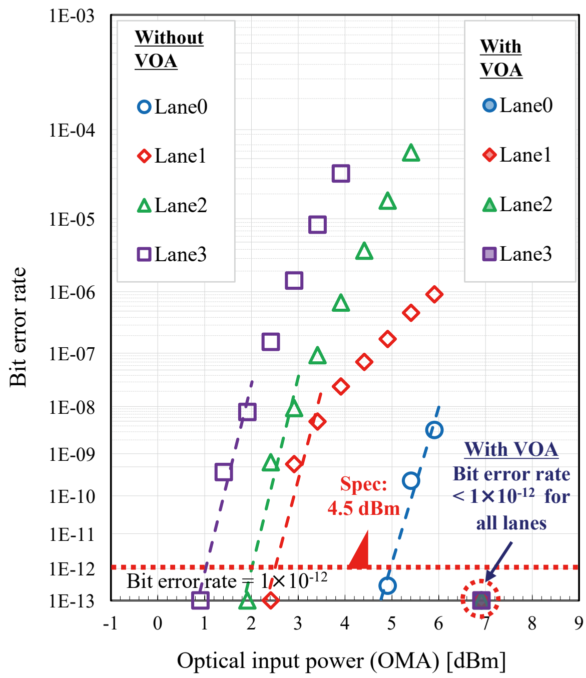


Fig. 7. Bit error rates at overload end

## 5. Efforts to Achieve Over 100 Gbit/s

### 5-1 Target specifications

We are working on application of the receiver module to 40 km reach, 400 Gbit/s transmission. More specifically, the modulation rate is 53.125 Gbaud, the modulation scheme is four-level pulse amplitude modulation (PAM4), and Gray-coded signals are used. Since PAM4 enables the transmission of information at a rate of two bits per symbol, as shown in Fig. 8, it becomes possible to send

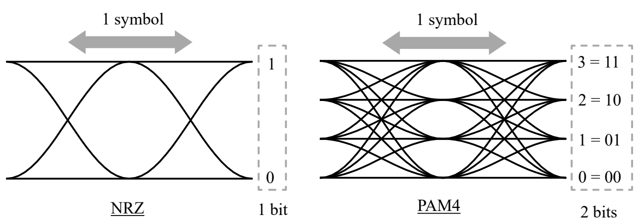


Fig. 8. Schematic diagrams of NRZ and PAM4 signals

double the amount of information compared to NRZ at the same symbol rate. Consequently, the transmission rate increases to 106.25 Gbit/s per wavelength, with the sum of four wavelengths being 425 Gbit/s. Table 2 shows the specifications required by 100G-ER1-40 for single-wavelength 40 km transmission, which are being standardized by the 100G Lambda MSA.(6)

Table 2. 100G-ER1-40 Specifications

| Parameter | | Specification | Unit |
|---|---|---|---|
| Modulation rate | | 53.125 ± 100 ppm | Gbaud |
| Modulation scheme | | PAM4 | - |
| Wavelength | | 1304.5 ~ 1317.5 | nm |
| Receiver sensitivity (OMA)‡ | TECQ*7 < 1.4 dB | ≤ -13.8 | dBm |
| | 1.4 dB ≤ TECQ ≤ 3.9 dB | ≤ -15.2 + TECQ | dBm |
| Overload (OMA)‡ | | ≥ -2.6 | dBm |

‡ Optical power at: Bit error rate = $2.4 \times 10^{-4}$

A 4-ch integrated receiver module(4) that supports 2 km reach 400 Gbit/s transmission has already been developed. We evaluated a receiver module based on the above design, mounting an SOA chip with improved linearity presently under development.

### 5-2 Receiver characteristics

A bit error rate evaluation was conducted at 25°C, using an optical transmitter module mounting a laser diode as the light source. The extinction ratio of the optical waveform was 5.6 dB; TECQ was 1.6 dB. Figure 9 presents the bit error rate measurement results. The signal pattern used was PRBS15Q.*6 The evaluation results met the specifications, with the minimum receiver sensitivity reaching −15.3 dBm at an SOA current of 80 mA and the overload being −1.9 dBm at an SOA current of 40 mA.

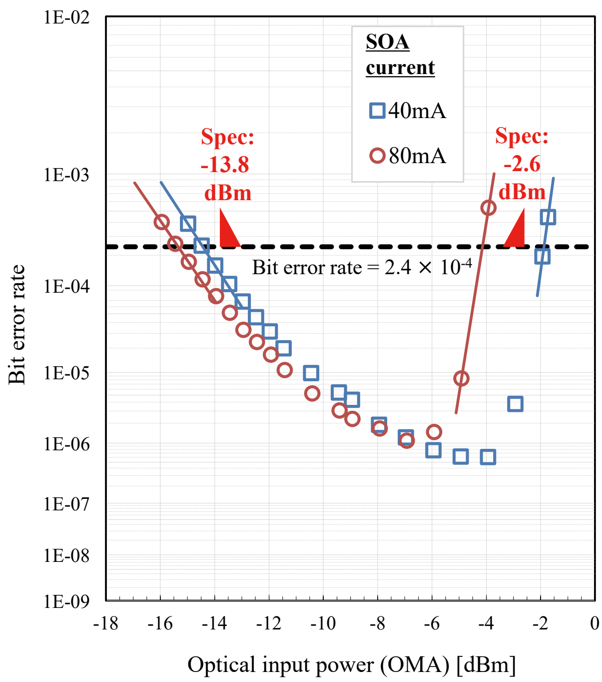


Fig. 9. Bit error rates observed when inputting 100 Gbit/s PAM4 signal

## 6. Conclusion

We have developed an SOA-incorporated 4-ch integrated receiver device that can be mounted on the small optical transceiver QSFP28 for 40 km reach, 100 Gbit/s transmission applications. By incorporating an in-house SOA chip, the receiver device achieves high receiver sensitivity and exhibits favorable characteristics at the minimum receiver sensitivity (OMA) of −25.9 dBm or less with 25.78125 Gbit/s NRZ signals. Furthermore, by incorporating a VOA, it proved itself able to meet the 100GBASE-ER4 specifications. It is highly likely that the receiver device will become suitable for 80 km reach applications when combined with forward error correction. In addition, by incorporating an SOA chip under development, it met the 100G-ER1-40 specifications for single-wavelength 40 km reach 100 Gbit/s transmission. This implies that it potentially supports transmission at 400 Gbit/s for 40 km in a 4-ch arrangement.

**Technical Terms**

*1 QSFP28/QSFP-DD: The Quad Small Form-factor Pluggable is an industry standard for small optical transceivers for over 100 Gbit/s applications. The QSFP-DD (double density) allows for 400 Gbit/s using four-wavelength optical signals at 100 Gbit/s transmission rate.

*2 LAN-WDM: A wavelength division multiplexing technology; LAN-WDM transmits four-wavelength signals separated from each other by a wavelength interval of approximately 5 nm through a single fiber.

*3 OMA: Optical modulation amplitude.

*4 Peltier module: A thermoelectric element; a Peltier module is a heating/cooling element utilizing the Peltier effect.

*5 MEMS: Micro-electro-mechanical systems; MEMS are devices integrating components such as microsensors, circuits, and moving parts on a semiconductor or other substrate.

*6 PRBS31/PRBS15Q: PRBS stands for pseudo-random bit sequence. PRBS31 uses an NRZ signal sequence with a pattern length of $2^{31} - 1$, while PRBS15Q uses a PAM4 symbol sequence with a pattern length of $2^{15} - 1$.

*7 TECQ: Transmitter eye closure quaternary; a measure of waveform quality.

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