Compact 4-ch Integrated Optical Receiver Module for 400-Gbit/s Transmission

Kazuaki MII*, Masanobu KAWAMURA, Kenichi NAKAYAMA, and Hiroshi HARA

There has been a strong demand for increasing data traffic resulting from the growth of advanced mobile terminals and the diversification of internet-based services. To address the needs, 100-Gbit/s optical transceivers have been used in optical communication systems. For further increase in data capacity, a new specification for 400-Gbit/s optical communications has been standardized, and optical transceivers applicable to it have been developed actively. We have developed a new compact receiver for 400-Gbit/s transmission based on the structure of our previous 100-Gbit/s receivers. This paper describes the design and typical characteristics of the new optical receiver.

Keywords: optical receiver module, 400G, crosstalk

1. Introduction

With the widespread use of the advanced communication terminals such as smartphones, a variety of internet contents have been developed and can be readily accessed. Utilization of big data and commercialization of 5G are advancing, with rising expectations for the Internet of Things (IoT). Against this background, data traffic is increasing rapidly. Consequently, there is a very strong demand for improved communication speeds and miniaturized communication devices.

Data centers are key network facilities, where optical communication systems operating at a transmission rate of 100 Gbit/s have been introduced. In these systems, optical transceivers are basic components. Small optical transceiver products, such as C form-factor pluggable (CFP4*1) and quad small form-factor pluggable (QSFP28*2), are widely used. In parallel with this situation, to realize additionally higher-capacity and faster communications, the 100G Lambda Multi-Source Agreement (MSA) Group(1) is standardizing a specification for 400-Gbit/s optical communications. Development of optical transceivers, such as QSFP-double density (DD)*2, is under way.

Sumitomo Electric Industries, Ltd. has developed compact four-channel (4-ch) integrated optical receiver modules that can be built into QSFP28 for 100-Gbit/s applications.(2)-(4) Next-generation 400-Gbit/s transmission requires even faster modules. We have developed a 4-ch integrated optical receiver module applicable to this high-speed transmission.

2. Target Specifications

Table 1 shows target specifications, which are based on the 400G-FR4*3 specification established by the MSA*4 for up to 2 km reaches. In optical communications, wavelength-division multiplexing (WDM) is used to increase transmission capacity. WDM is a technique to transmit several wavelengths of light through a single mode fiber. In 400G-FR4, the four wavelengths of the coarse wavelength-division multiplexing (CWDM*5) grid in the 1300-nm band is utilized. Its symbol rate is 53.125 Gbaud. The modulation scheme is four-level pulse amplitude modulation (PAM4) using Gray codes. PAM4 can transmit two bits per symbol, as shown in Fig. 1. Therefore, the data rate is 106.25 Gbit/s per wavelength, with a total of four wavelengths reaching 425 Gbit/s.

Table 1. Specifications for optical receiver

Parameter		Spec	Unit
Symbol rate		53.125 ± 100 ppm	Gbaud
Modulation Scheme		PAM4	-
Wavelength	Lane 0	1264.5~1277.5	nm
	Lane 1	1284.5~1297.5	
	Lane 2	1304.5~1317.5	
	Lane 3	1324.5~1337.5	
Receive power (OMA*6)† (max.)		≥ 3.7	dBm
Lane-to-lane power difference (OMA)		≤ 4.1	dB
Receiver sensitivity (OMA)†		Equation (1)	dBm
Optical return loss		≥ 26	dB

† Optical power at: Bit error rate = 2.4×10^{-4}

$$\text{Receiver sensitivity} = \begin{cases} -4.6 \ (SECQ^{*7} \leq 1.4) \\ SECQ - 6.0 \ (1.4 \leq SECQ \leq 3.4) \end{cases} \quad \cdots\cdots (1)$$

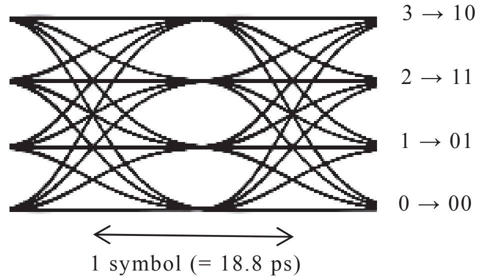


Fig. 1. PAM4 signal

3. Design of 4-ch Integrated Optical Receiver Module

3-1 Module structure

Photo 1 shows the external appearance of the 4-ch integrated optical receiver module. The package size is 15.4 mm × 6.7 mm × 5.3 mm, which can be built into a compact QSFP-DD optical transceiver. Figure 2 shows the structure of the optical receiver module. The module has a receptacle that is connected to an optical fiber and flexible printed circuits (FPCs) connected to a printed circuit board of an optical transceiver. Photodiodes (PDs), a transimpedance amplifier (TIA), and other chip components, as well as an optical de-multiplexer and other optical components, are mounted in a hermetically sealed package. The back-illuminated PDs are flip chip-mounted*[8] on a carrier. The carrier, the TIA and the package are wire-connected. A monolithic lens formed on the back of the PD enlarges the photosensitive area to provide a wide assembly tolerance.

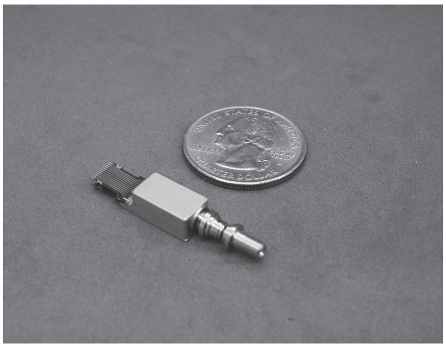


Photo 1. 4-ch integrated optical receiver module

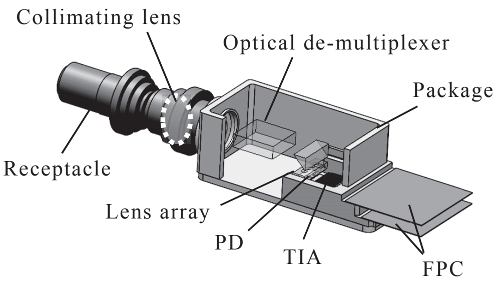


Fig. 2. Structure of 4-ch integrated optical receiver module

The collimating lens converts optical signals entering the receptacle into parallel beams, which are repeatedly reflected in the optical de-multiplexer, as shown in Fig. 3. Filters separate the beams according to wavelengths. The separated beams pass the lens array and couple with the PD in each lane. The PDs convert optical signals into electrical currents, which the TIA converts into amplified voltage signals. These differential electrical signals are sent to the optical transceiver via the package and the FPCs.

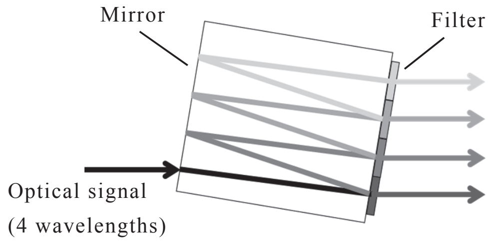


Fig. 3. Optical de-multiplexer

3-2 High-frequency design

In the input block of the TIA, the carrier that has PDs mounted connects to the TIA via gold wires. The inductance of the wire, L_1, and the parasitic capacitance of the carrier, C_1, form a resonance circuit.(5) A simplified equivalent circuit of the resonance circuit would be the one illustrated in Fig. 4 without the additional path. In this condition, the resonance frequency is expressed as follows.

$$fr = \frac{1}{2\pi\sqrt{L_1C_1}} \quad \cdots\cdots (2)$$

Given that L_1 is 0.2 nH and C_1 is 75 fF, the resonance frequency would become roughly 41 GHz, causing a degradation of waveforms in the transmission of 53 Gbaud signals. Moreover, the signals would interfere with other lanes and degrade their signal integrity due to crosstalk. As a solution to this problem, the additional path shown in Fig. 4 has been provided to the carrier to form a parallel resonance circuit consisting of L_1, L_2, and C_1. With this configuration, the resonance frequency is expressed as follows.

$$fr = \frac{1}{2\pi}\sqrt{\frac{L_1 + L_2}{L_1L_2C_1}} \quad \cdots\cdots (3)$$

By reducing inductance L_2, it is possible to increase the resonance frequency independent of L_1 of the wire between the carrier and the TIA.

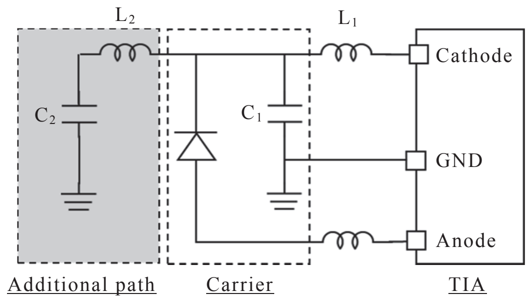


Fig. 4. Equivalent circuit

4. Characteristics of Optical Receiver Module

4-1 Optical characteristics

Figure 5 shows the responsivity spectrum of the 4-ch integrated optical receiver module. The optical de-multiplexer mounted in this module is compatible with the CWDM wavelength grid. In the wavelength range of each lane, which is indicated with the dashed lines in the figure, the receiver obtains a responsivity of 0.6 A/W or more and the fluctuations of responsivity are controlled below 0.5 dB. The monolithic lens-integrated PD structure and the optical de-multiplexer incorporating a thin-film filter achieve the low-loss optical system. In addition, the lane-to-lane isolation is 25 dB and more, and the optical return loss is 26 dB and more.

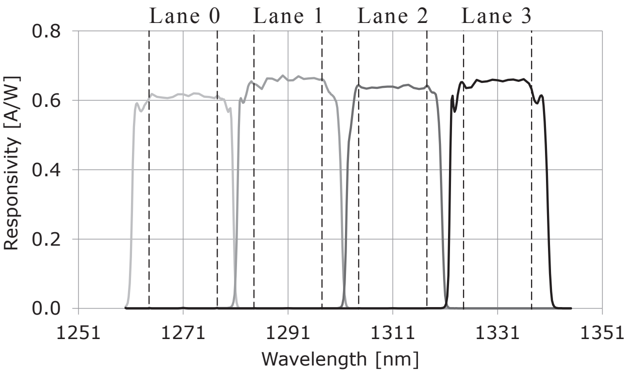


Fig. 5. Responsivity spectrum

4-2 Frequency response

Figure 6 shows frequency characteristics of optical-to-electrical response normalized at 1 GHz. The -3 dB bandwidth is wide at 40 GHz or higher, and lane-to-lane variation is small. No resonance occurs below 60 GHz as a result of shifting the resonance frequency to higher frequencies. Figure 7 shows frequency dependence of crosstalk, indicating the intensity of the optical signal of Lane x (x = 0, 1, or 2) being output as a Lane 3 electrical signal. Even crosstalk between adjacent Lane 2 and Lane 3 is fairly low at -20 dB or below. Transmission characteristics are affected very little by lane-to-lane crosstalk, as discussed in 4-3.

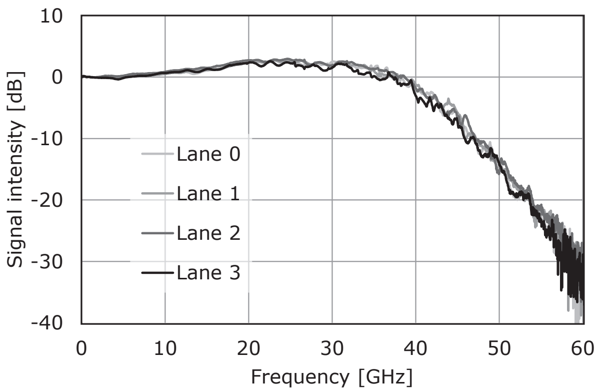


Fig. 6. Frequency characteristics of optical-to-electrical response

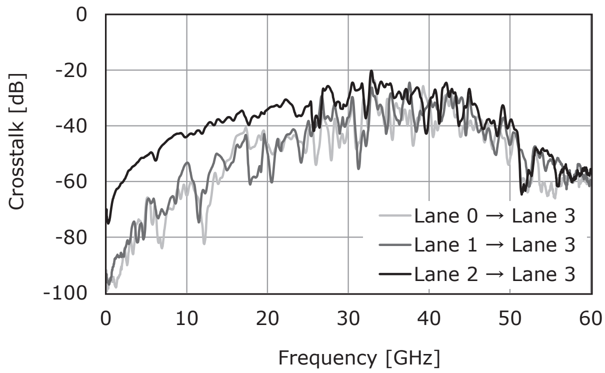
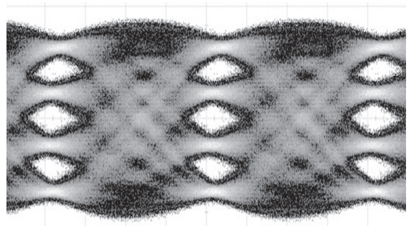


Fig. 7. Frequency dependence of crosstalk

4-3 Optical receiving characteristics

Electrical waveforms and the bit error rate were evaluated when inputting 53 Gbaud PAM4 signals at a module temperature of 25ºC. An optical transceiver with an electro-absorption modulated laser generated optical signals. The extinction ratio of optical signals was 5.4 dB, and the stressed eye closure for PAM4 (SECQ)*[7] was 2.0 dB. Figure 8 shows waveforms observed by processing the module's output waveforms with an 11-tap feed forward equalizer (FFE)*[9] at an optical power of -9 dBm and a signal pattern of pseudo-random bit sequence (PRBS)15Q.*[10] The obtained waveforms exhibit good eye opening.



53.125 Gbaud, PRBS15Q, FFE (11 taps)

Fig. 8. Electrical waveforms

Figure 9 shows measurement results of bit error rate. PRBS31Q*[10] was used as a signal pattern. The receiver sensitivity (OMA) that ensures a bit error rate of 2.4×10^{-4} is -4.0 dBm or less according to Equation (1). The receiver sensitivity is -10.2 dBm, and the maximum received power is 4.9 dBm, adequately meeting the specification. To evaluate the influence of crosstalk, the measured lane was input a 4.1 dB greater optical power than that of the other lanes according to the lane-to-lane power difference (OMA) shown in Table 1. The evaluation results reveal that the receiver sensitivity degraded only 0.1 dB or less due to lane-to-lane crosstalk, as surmised from the frequency characteristics.

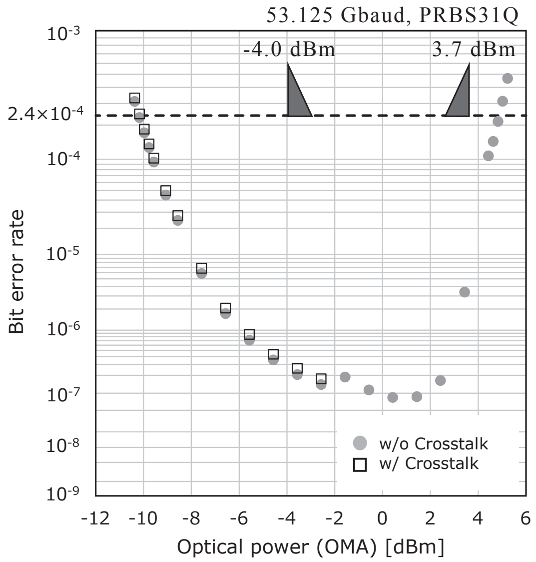


Fig. 9. Bit error rate

5. Conclusion

We have developed a 4-ch integrated optical receiver module that can be built into a compact optical transceiver for applications using a data rate of 400 Gbit/s for 2 km reaches. By optimizing the design for high-frequency characteristics, the receiver module demonstrates excellent characteristics when receiving 53 Gbaud PAM4 signals, wherein a receiver sensitivity is -10.2 dBm and lane-to-lane crosstalk is 0.1 dB or less. This result verifies that the new receiver satisfies the 400G-FR4 specification.

Technical Terms

*1 CFP4: C form-factor pluggable: An industry standard for optical transceivers operating faster than 100 Gbit/s.

*2 QSFP28/QSFP-DD: Quad small form-factor pluggable: An industry standard for compact optical transceivers operating faster than 100 Gbit/s. QSFP-double density (DD) achieves 400 Gbit/s by using four different wavelengths at a data rate of 100 Gbit/s per optical signal.

*3 400G-FR4: A specification for optical interface for 400-Gbit/s optical transceivers that communicate over single mode fibers of length from 2 m to 2 km.

*4 MSA: Multi-source agreement: A common component specification developed with the aim of ensuring mutual compatibility between vendors.

*5 CWDM: Coarse wavelength-division multiplexing: A wavelength-division multiplexing technique that uses wavelengths spaced 20 nm apart.

*6 OMA: Optical modulation amplitude.

*7 SECQ: Stressed eye closure for PAM4: A measure of the optical waveform.

*8 Flip chip-mounting: A method for mounting components on substrates. Components and circuits are electrically connected using electrodes made of conductive materials instead of using electric wires.

*9 FFE: Feed forward equalizer: A technique to compensate signal degradation.

*10 PRBS15Q/PRBS31Q: PRBSnQ denotes a PAM4 symbol sequence whose pattern length is 2^n - 1. PRBS is an abbreviation of pseudo-random bit sequence.

References

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Contributors

The lead author is indicated by an asterisk (*).

K. MII*
• Assistant Manager, Transmission Devices Laboratory

M. KAWAMURA
• Assistant General Manager, Transmission Devices Laboratory

K. NAKAYAMA
• Transmission Devices Laboratory

H. HARA
• Group Manager, Transmission Devices Laboratory