Integrated ROSA with High-Sensitivity APD Chips for up to 400 Gbit/s Communication

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In response to market expectations for 200 Gbit/s and 400 Gbit/s optical devices, we have developed a new compact receiver with four avalanche photodiodes and an integrated optical de-multiplexer for 40 km operating distance applications. This receiver is based on the structure of our previous 40 Gbit/s and 100 Gbit/s receivers and employs newly developed avalanche photodiodes for high responsibility. This paper presents the design and performance of the receiver, including its receiver sensitivity in 53 Gbit/s PAM4 (Pulse amplitude modulation 4) signal transmission.

Keywords: beyond 100G, receiver, high integration, APD

1. Introduction

Expansion of long term evolution (LTE)*1 and other high-speed wireless network services and the recent evolutionary progress of mobile terminals have made it easy for us to access large-volume data such as video contents. As can be seen from the fact that big data, IoT, and many other keywords are used in the business world, the dependence of society on telecommunications is increasing more and more.

In such a social situation, optical transceivers with a data rate of 100 Gbit/s are used mainly for building the fiber-optic networks. The Centum Form-factor Pluggable (CFP)*2, compact CFP4*2, and Quad Small Form-factor Pluggable 28 (QSFP28)*3 are shown in Fig. 1 as typical examples of 100 Gbit/s optical transceivers. Meanwhile, market needs for data rate are gradually shifting to 200 Gbit/s and 400 Gbit/s. Hence, the next-generation optical transceivers such as CFP8*2 and QSFP-DD*3 have been developed.

Sumitomo Electric Industries, Ltd. has developed and supplied compact receivers comprising four photodiodes and an optical de-multiplexer (4-channel integrated receiver).(1)-(3) These receivers have a width of 6.7 mm and can receive four signal beams of different wavelengths, so that they can be built into QSFP28 transceivers. In response to market needs for high data rates of over 200 Gbit/s and operating distances of over 20 km, we have developed an integrated receiver equipped with our original high-sensitivity avalanche photodiodes (APDs). For the development, we used the 4-channel integrated receiver design technologies we had accumulated until then.

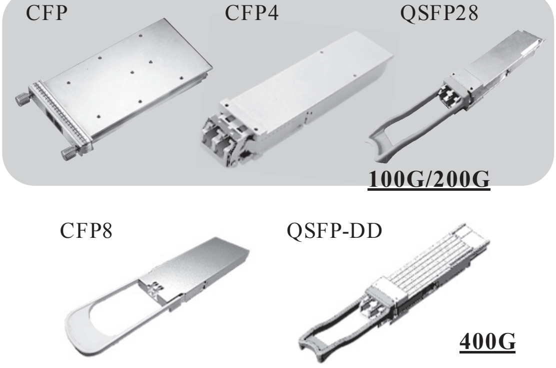

Fig. 1. External Appearance of Over-100 Gbit/s Optical Transceivers

2. Structure of 4-Channel APD Integrated Receiver

2-1 Overall structure

The external appearance of 4-channel integrated receiver series is shown in Fig. 2, while their typical structure is schematically illustrated in Fig. 3. Adoption of the receptacle, package, and other components that had already

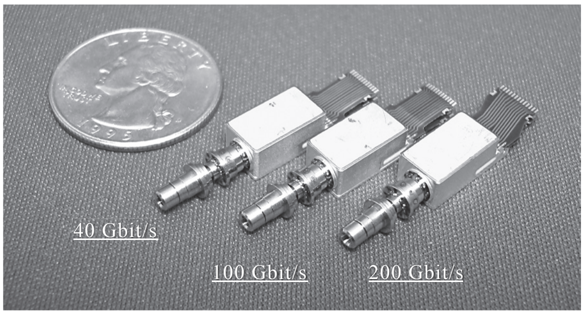

Fig. 2. External Appearance of 4-channel Integrated Receiver Series

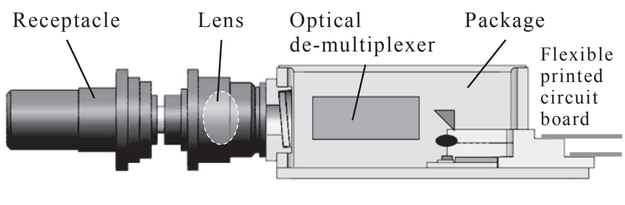

Fig. 3. Schematic Illustration of the Structure of 4-channel Integrated Receiver

been used in our conventional 4-channel integrated receivers has made the newly developed receiver possible to be housed in a compact QSFP28 optical transceiver.

Figure 4 shows schematically the optical system of the 4-channel APD integrated receiver. A beam consisting of four signal beams of different wavelengths is collimated by the lens built in the receptacle outside the package, and then separated spatially into four signal beams by an optical de-multiplexer mounted in the package. The optical de-multiplexer is made up of band-pass filters and a mirror facing each other. Each of the band-pass filter transmits only a signal beam of a specific wavelength. When transmitted and reflected repeatedly between the band-pass filters and mirror, the multiplexed optical beam is de-multiplexed into four signal beams.

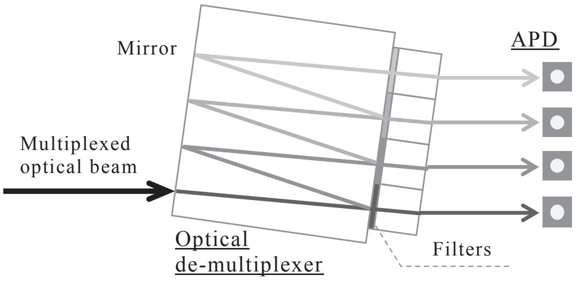

Fig. 4. Schematic Illustration of the Optical System of 4-channel APD Integrated Receiver

Each signal beam is focused on the corresponding APD that we originally designed. This APD is characterized by back-illuminated structure, monolithically integrated lens, and high responsivity as described later. The functional block diagram of the electrical signal system is shown in Fig. 5. Each signal beam is photoelectrically converted into an electric signal by the corresponding APD

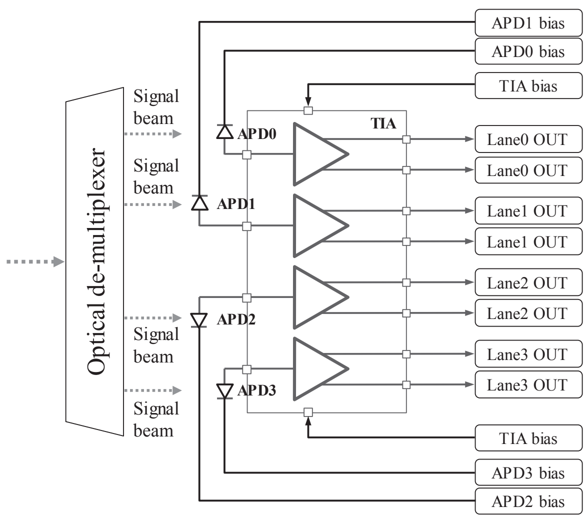

Fig. 5. Functional Block Diagram of 4-channel APD Integrated Receiver

and amplified by a trans-impedance amplifier (TIA). These signals are subsequently sent to the optical transceiver through the transmission lines in the package and the flexible printed circuit board.

To ensure a data rate of over-50 Gbit/s per signal beam, the 4-level pulse amplitude modulation (PAM4) method was standardized as the IEEE802.3bs specification for 200 Gbit/s and 400 Gbit/s applications instead of conventional non-return to zero (NRZ) signals.(4) An NRZ signal uses a single symbol to transmit 1-bit information, whereas a PAM4 signal contains 2 bits of information per symbol as shown in Fig. 6. Therefore, it can double the transmissible quantity of information as compared with an NRZ signal without changing the symbol rate.

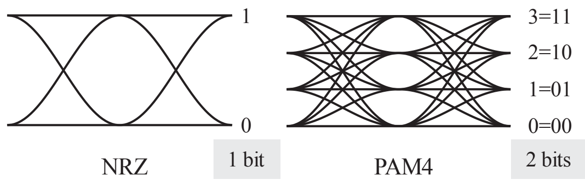

Fig. 6. Schematic Illustration of NRZ and PAM4 Signals with Same Symbol rate

2-2 Structure of APD

The external appearance and schematic view of the cross-section structure of the fabricated APD chip are shown in Fig. 7. This APD chip achieved high-speed operation by optimizing the CR time constant, carrier-transit time, and avalanche build-up time. In order to obtain a higher optical coupling efficiency, we adopted a back-illuminated structure with a monolithic lens because of the small photosensitive area to reduce the chip capacitance. In addition, solder bumps were formed on the chip to make flip chip mounting*4 easy on a submount. On the other hand, to shorten the carrier-transit time and avalanche build-up time, we optimized the thickness and carrier concentration of both the optical absorption layer and avalanche multiplication layer based on the electric field design of the semiconductor structure. These semiconductor layers were grown by using the organometallic vapor phase epitaxy method, which can control the thickness and dopant concentration of each layer with high accuracy.

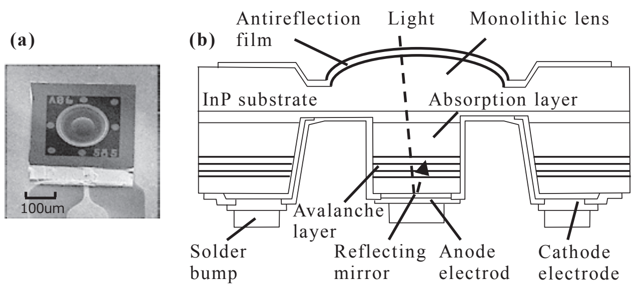

Fig. 7. (a) External Appearance and (b) Construction of APD Chip

Although reducing the absorption layer thickness is effective to shorten the carrier transit time, it leads to low optical responsivity of the APD. To prevent the responsivity decrease, our APD chip has a reflecting mirror that returns optical signals passing through the absorption region without being absorbed. We designed the electrode metal so that it also functions as a reflecting mirror to prevent complication of the APD chip and thereby enhance its production efficiency.

2-3 Characteristics of APD

Figure 8 shows the current-voltage (I-V) characteristics of the APD chip at its temperature of 25°C and optical input power of -27 dBm. As shown in this figure, our APD chip demonstrated a low dark current of 400 nA or less at a bias voltage equivalent to 90% of breakdown voltage, and a large gain of 30 or more was obtained in the maximum multiplication factor. Figure 9 shows the optical responsivity profiles in the photosensitive area at an APD chip temperature of 25°C and a multiplication factor of 10, which were normalized with the maximum responsivity of existing chips without a reflecting mirror. As shown, the addition of a reflecting mirror increased the maximum responsivity by 30%. Thus, our APD chip has achieved both the larger photosensitive area and higher optical responsivity with a monolithic lens and reflecting mirror.

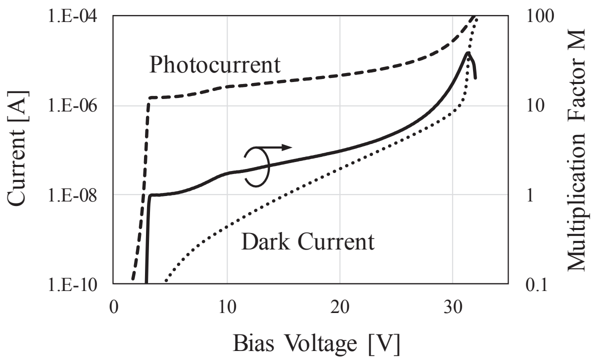

Fig. 8. I-V Characteristics of APD

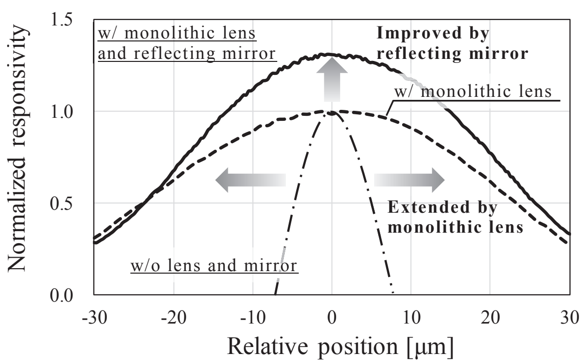

Fig. 9. Responsivity Profiles of APD

3. Target Specifications of Receiver to Be Developed

Prior to the development of the 4-channel APD integrated receiver, we set up the target specifications as shown in Table 1. In the process of setting up our original specifications, we referred to the applicable IEEE standards and 4WDM[(5)] Multi-Source Agreement (MSA)*[5] while taking market needs into account.

Table 1. Target Specifications

	100 Gbit/s	200 Gbit/s	Unit
Modulation method	NRZ	PAM4	
Data rate per signal	25.78125	53.125	Gbit/s
Wavelength	1294.53-1296.59		nm
	1299.02-1301.09		
	1303.54-1305.63		
	1308.09-1310.19		
Sensitivity, OMA*[6]	< -18.5†	< -15.0‡	dBm

†: Defined as the input power at a bit error rate of 5×10^{-5}
‡: Defined as the input power at a bit error rate of 2×10^{-4}

4. Receiver Performance

4-1 Responsivity characteristics

The responsivity spectrum of the 4-channel APD integrated receiver is shown in Fig. 10. The receiver comprises an optical de-multiplexer that conforms to the wavelength grid specified by the IEEE. The responsivity was measured at an average optical input power of -20 dBm and a multiplication factor of 1.

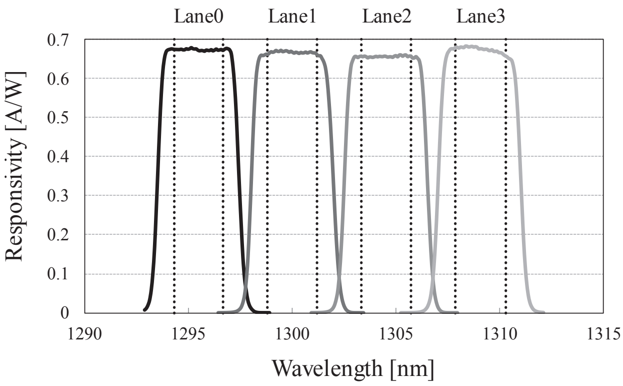

Fig. 10. Responsivity Spectrum of 4-channel Integrated APD Receiver

In the wavelength range of each lane, the receiver attained a responsivity of 0.65 A/W or more and has well-controlled fluctuation of the responsivity up to 0.5 dB. This means that all of the four signal beams are coupled to the photosensitive area of corresponding APD chips at a high efficiency. These favorable characteristics are owed to our original APD chip with monolithic lens and reflecting mirror.

4-2 Total harmonic distortion and output amplitude

Figure 11 shows the dependence of the total harmonic distortion (THD) and output amplitude on the average optical input power. These were measured by using a light with a modulation frequency of 1 GHz and a modulation percentage of 30%. The THD of the receiver was 1% or less when the input power was 0 dBm or less, while it was 2% or less even when the input power was +2 dBm. The output amplitude increased monotonically in a range of up to -15 dBm, while it remained at a nearly constant value until the input power reached +2 dBm because of the gain adjustment function of the TIA. These characteristics were attributable to the high linearity of the receiver and were sufficient for processing PAM4 signals in the transceiver.

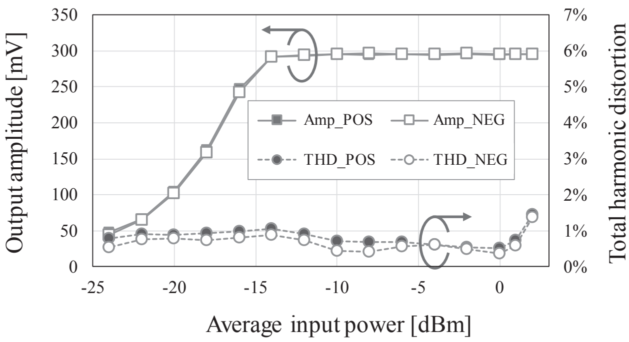

Fig. 11. Total Harmonic Distortion and Output Amplitude

4-3 Receiver sensitivity characteristics

The bit error rates for 25.78125 Gbit/s NRZ signals (PRBS2^{31}-1) at a receiver temperature of 25°C are shown in Fig. 12. These bit error rates were measured when there was a crosstalk caused by other three lanes. It was confirmed from this figure that the receiver has excellent receiver sensitivity characteristics. In particular, the receiver sensitivity defined as optical modulation amplitude (OMA) at a bit error rate of 5×10^{-5} was measured to be -23 dBm or less with a margin of 4.5 dB or more for the target value of -18.5 dBm. It was also confirmed that the crosstalk penalty was 0.5 dB or less.

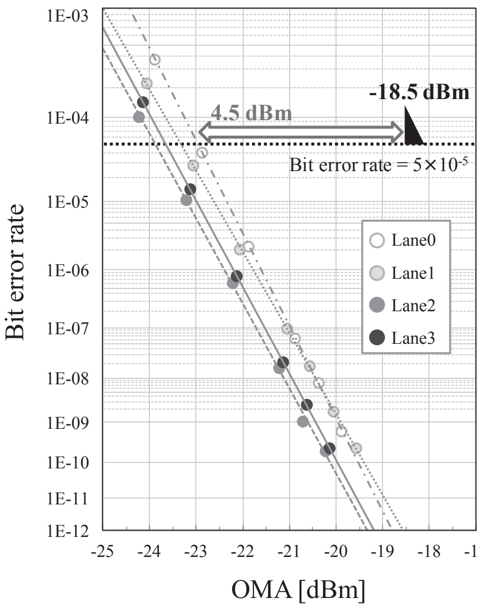

Fig. 12. Bit Error Rate for NRZ Signal at 25.78125 Gbit/s

The bit error rates for 53.125 Gbit/s PAM4 signals (PRBS2^{31}-1) at a receiver temperature of 25°C are shown in Fig. 13. These bit error rates were measured when no crosstalk was given from the other three lanes. A 4-channel integrated transmitter we have newly developed was used as the optical source.(6) This transmitter integrates four laser diodes attached with an electro absorption modulator into a package. The receiver sensitivity, which is defined as OMA at a bit error rate of 2×10^{-4} without forward error correction (FEC), was measured to be -17 dBm or less on all lanes, verifying that the receiver sensitivity meets the target value. Regarding the receiver sensitivity at a bit error rate of 1×10^{-12} with FEC, the receiver also exhibited an acceptable value of -17 dBm or less.

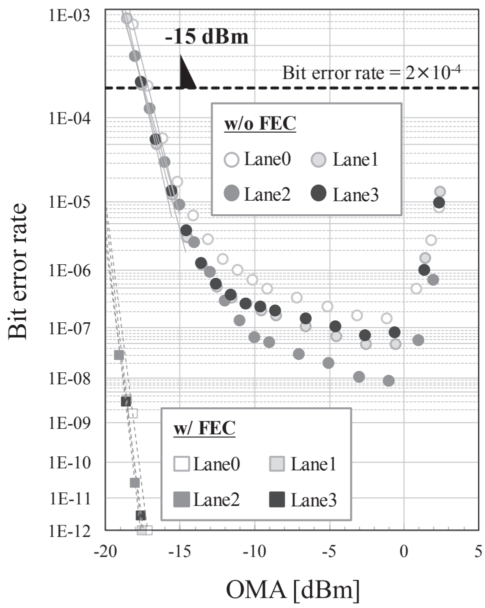

Fig. 13. Bit Error Rate for PAM4 Signal at 53.125 Gbit/s

4-4 Fiber transmission characteristics

The bit error rates for 53.125 Gbit/s PAM4 signals (PRBS2^{31}-1) after transmission over 0, 20, and 40 km at a receiver temperature of 25°C are shown in Fig. 14. The same 4-channel integrated transmitter mentioned in the preceding section was also used as the optical source. Deterioration of the receiver sensitivity after transmission over 40 km was 0.1 dB or less for both with and without FEC. This result verified that the new receiver can be used for fiber transmission of 53.125 Gbit/s PAM4 signals over a distance of 40 km or more.

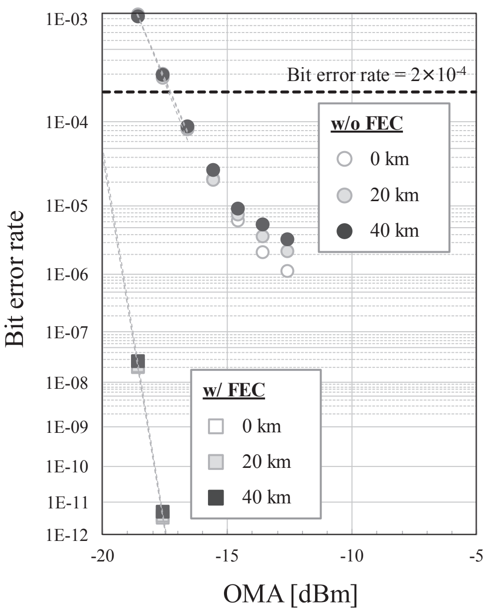

Fig. 14. Bit Error Rate after Fiber Transmission

5. Conclusion

We have developed a 4-channel APD integrated receiver that can be built in a 200 Gbit/s optical transceiver for 40 km or longer distance applications. Equipped with our original APD chips, this receiver has excellent receiver sensitivity and can be manufactured at a very high efficiency. In particular, the receiver sensitivity is -23 dBm or less for 25.78125 Gbit/s NRZ signals and -17 dBm or less for 53.125 Gbit/s PAM4 signals. Receiver sensitivity deterioration after transmission over 40 km is 0.1 dB or less. When equipped with an optical de-multiplexer that complies with 1274/1278/1282/1287 nm wavelength grid, the new receiver can be mounted in the CFP8 transceiver for 400 Gbit/s applications.

Technical Terms

∗1 Long term evolution (LTE): A standard for cellular phone communication. LTE is also expressed as 4G.

∗2 CFP/CFP4/CFP8: CFP is an abbreviation for Centum gigabit Form-factor Pluggable, an industry standard for over-100 Gbit/s compact optical transceivers. CFP8 achieves a data rate of 400 Gbit/s by transmitting eight wavelength signal beams at 50 Gbit/s.

∗3 QSFP28/QSFP-DD: QSFP is an abbreviation for Quad Small Form-factor Pluggable. QSFP28 and QSFP-DD (double density) achieves a data rate of 100 Gbit/s and 400 Gbit/s by transmitting four signal beams of different wavelengths at 25 Gbit/s and 100 Gbit/s.

∗4 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.

∗5 Multi-Source Agreement (MSA): An industrial standard for parts specifications established by parts suppliers.

∗6 Optical Modulation Amplitude (OMA): OMA is defined as the difference between high and low optical power levels.

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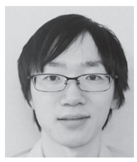

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