56-Gbit/s 40-km Optical-amplifier-less Transmission with NRZ Format Using High-speed Avalanche Photodiodes

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Abstract: We present the world’s first demonstration 56-Gbit/s 40-km transmission with NRZ format using a high-speed avalanche-photodiode-based optical receiver. The receiver exhibited a minimum sensitivity of -20.8 dBm after 40-km transmission at the BER of 2.3×10^-4.

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1. Introduction

100-Gbit/s/λ optical interfaces are attracting strong interest to cope with the significant growth of data traffic in client networks. In 400-Gbit/s Ethernet (400GbE) systems, a 50-Gbaud 4-level pulse-amplitude modulation (PAM4) format, or a 100-Gbit/s/λ interface, was standardized for 500-m applications [1]. However, for 2- and 10-km applications, 25-Gbaud PAM4 format, or a 50-Gbit/s/λ interface with an increased lane count, was standardized due to a lack of sensitivity and speed in an optical receiver. As seen in the 400GbE case, future client network systems will face a technical challenge in trying to simultaneously improve both the operating baud rate and the transmission distance. While a higher baud rate contributes to scaling down a transceiver size and minimizing the power consumption of the transceiver because it can reduce the number of lanes against a given transmission capacity, the transmission distance becomes shorter due to the lack of output power of the transmitter, the sensitivity of the receiver, and the impact of the dispersion of the optical fiber. At present, the 25-Gbaud NRZ format can realize a transmission distance of up to 40 km, which is enough to cover inter-building networks. There are currently no technologies to achieve both a 100-Gbit/s/λ interface and 40-km transmission regardless of modulation format. In order to cover up to 40-km transmission with a 100-Gbit/s/λ interface, it is necessary to achieve at least 50-Gbaud operation of an optical receiver along with high sensitivity when using the PAM4 format as a possible multi-level format. An Avalanche photodiode (APD) is a promising candidate to meet these requirements owing to its internal gain and a chip size and power consumption comparable to a conventional pin-PD. Previously, a preliminary demonstration of 50-Gbaud APD has been reported at back-to-back condition [2]. However, there is no report on a 50-Gbaud 40-km transmission experiment. If transmission up to 40 km with a baud rate of over 50 Gbaud is achieved with APDs, a 100-Gbit/s/λ interface will be feasible. In this paper, we present a 56-Gbit/s NRZ 40-km transmission without optical amplifiers using our developed high-speed APD optical receiver for the first time.

2. Design of APD and its optical receiver

The proposed APD has an inverted p-down structure that we previously reported [2-3], as shown here in Fig. 1(a). The epitaxial layers including p-type contact, hybrid absorption, p-type filed control, avalanche, n-type field control, edge-field buffer, and n-type contact layers were grown on a semi-insulating InP substrate by MOCVD method.
For ensuring high speed and high responsivity, we used a 600-nm-thick hybrid absorption layer with a combination of undoped and p-doped InGaAs layers and optimized the ratio of thickness of the p-doped layer to that of the whole absorption layer so that the hybrid absorption layer has a minimum carrier transit time. The optimal thickness of the neutral absorption layer for the 600-nm thick hybrid absorption layer is 250 nm. However, if we set the thickness of the p-doped layer to 250 nm, about 50-nm of that layer will be depleted at the operating bias voltage. Thus, we set the thickness of the p-doped absorption layer to 300 nm. Thanks to the hybrid absorption layer, our fabricated APD exhibits a large $f_{3dB}$ of 35 GHz at $M = 3$ and a high responsivity of 0.7 A/W at a gain of unity. We used a 90-nm InAlAs avalanche layer exhibiting a gain-bandwidth product of 270 GHz, which is advantageous for high-speed and large-gain operation. The APD has an anti-reflecting coat optimized for the 1.3-μm wavelength on the backside of the substrate. Figure 1 (b) shows the I-V characteristics and gain curve of the APD. The gain rises from 12 V and continuously increases to 30 V. The APD exhibits a gain of 5 at the bias voltage of 26 V.

The fabricated optical receiver has GPPO electrical outputs with butterfly configuration. The APD chip is mounted on the receiver module together with an InP-based trans-impedance amplifier (TIA) with an $f_{3dB}$ of 27 GHz. In order to minimize the electrical loss and bandwidth degradation in the receiver module, we optimized the design of a transmission line connecting the APD and TIA and their arrangement in the module. The optical signal launched from a fiber is introduced to the backside of the APD chip.

3. Measurement setup

The measurement setup is shown in Fig. 2. As a transmitter, we used a 1304-nm wavelength electro-absorption modulator integrated DFB-laser (EML) [4] with a launch power of +2.3 dBm. The extinction ratio at 56 Gbit/s was 6.88 dB. The pseudo-random bit sequences (PRBSs) were set to $2^{15}-1$. Optical signals were injected into the APD optical receiver through a single-mode fiber (SMF). The receiver sensitivity was experimentally determined with a variable optical attenuator (VOA) inserted in front of the APD optical receiver. The electrical output signals from the APD optical receiver were sampled and digitized with a 160-GSample/s real-time storage oscilloscope with an analog bandwidth of 64 GHz. The bit error rate (BER) was evaluated with offline digital signal processing in which we used an adaptive feed-forward equalizer (FFE). The inset of Fig. 2 shows an eye diagram of the optical signals output from the EML.

![Fig. 2 Experimental setup for BER measurement](Tu2D.1.pdf)

4. Bit-error-rate characteristics

Figure 3 shows the $f_{3dB}$ of the fabricated APD and the BER of the APD optical receiver against APD gain. In the BER measurement, the input power of the optical signal was set to -19 dBm. The minimum BER of $2.89 \times 10^{-6}$ of the APD optical receiver was obtained at an APD gain of 5, where the $f_{3dB}$ of the APD was 30 GHz. The responsivity at the gain providing the minimum BER was 3.45 A/W. Although the larger gain of the APD provided better responsivity of APD, the BER degraded due to inferior $f_{3dB}$ owing to the limitation of GBP.

Figure 4 (a) and (b) shows the BER characteristics of the APD optical receiver. In Fig. 4 (a), the BER characteristics with conditions of back-to-back and after 40-km transmission are compared. The number of taps used for FFE was 17 for both conditions. No significant penalty can be seen under either condition. For 40-km transmission, the BER reached $2.3 \times 10^{-4}$, which is low enough for error-free operation if we assume the KP4 FEC [5] at a received power of -20.8 dBm. Figure 4 (b) shows the BER characteristics difference between 9 and 17 taps after 40-km transmission conditions. The received power of -20.0 dBm at the BER of $2.3 \times 10^{-4}$ was achieved even after the relatively small number of 9 taps along with a small penalty in the receiver sensitivity. The link budget reached as large as 22.3-23.1 dB, which was estimated with the launch power of the used transmitter and the
obtained minimum receiver sensitivity for both tap cases. These results indicate that our APD optical receiver has potential for 56-Gbit/s NRZ 40-km transmission without power increase due to the electrical signal processing.

5. Conclusion
We demonstrated the world’s first 56-Gbit/s NRZ 40-km transmission without an optical amplifier by using high-speed APD. The APD with the inverted p-down structure exhibited an $f_{3dB}$ of 30 GHz and a responsivity of 3.45 A/W at operating condition. The APD optical receiver demonstrated a BER of $2.3 \times 10^{-4}$ at the received power of -20.8 dBm after 40-km transmission. Furthermore, the APD optical receiver showed only a marginal penalty when the number of taps was reduced from 17 to 9. This indicates the potential of our APD for both middle-reach and low-power applications using a high baud rate of 56 Gbit/s.

6. References