Dispersion tolerance of 100-Gbit/s PAM4 optical link utilizing high-speed avalanche photodiode receiver

Toshihide Yoshimatsu<sup>1</sup><sup>a)</sup>, Masahiro Nada<sup>2</sup>, Shigeru Kanazawa<sup>1</sup>, Fumito Nakajima<sup>2</sup>, Hideaki Matsuzaki<sup>2</sup>, and Kimikazu Sano<sup>1</sup>

<sup>1</sup>NTT Device Innovation Center, NTT Corporation, 3–1 Morinosato Wakamiya, Atsugi, Kanagawa 243–0198, Japan
<sup>2</sup>NTT Device Technology Labs, NTT Corporation, 3–1 Morinosato Wakamiya, Atsugi, Kanagawa 243–0198, Japan

<sup>a)</sup> toshihide.yoshimatsu.xb@hco.ntt.co.jp

Abstract: For the purpose of developing a 4λ × 100-Gbit/s PAM4 10-km optical link, the dispersion tolerance through single mode fiber was experimentally investigated with a high-speed avalanche photodiode (APD) receiver. The power penalty was less than 1 dB over the LAN-WDM dispersion range.

Keywords: avalanche photodiodes, optical receivers, pulse amplitude modulation, optical communication

Classification: Integrated optoelectronics

References

[1] 100G Lambda MSA: http://100glambda.com/.
[2] M. Nada, et al.: “56-Gbit/s 40-km optical-amplifier-less transmission with NRZ format using high-speed avalanche photodiodes,” Proc. OFC (2016) Tu2D.1.
[3] M. Nada, et al.: “106-Gbit/s PAM4 40-km transmission using an avalanche photodiode with 42-GHz bandwidth,” Proc. OFC (2018) W4D.2.
[4] M. Nada, et al.: “Responsivity-bandwidth limit of avalanche photodiodes: Toward future Ethernet systems,” IEEE J. Sel. Top. Quantum Electron. 24 (2018) 3800811 (DOI: 10.1109/JSTQE.2017.2754361).
[5] W. Way, et al.: “Improvement results for both 56 and 112 Gb/s PAM4 signals,” http://www.ieee802.org/3/bs/public/15_01/way_3bs_01a_0115.pdf.
[6] H. F. Liu, et al.: “Technical feasibility study of 106 Gb/s PAM4 optical link,” http://www.ieee802.org/3/cd/public/Sept16/liu_3cd_01_0916.pdf.
[7] IEEE: 802.3-2015 (2015) (DOI: 10.1109/IEEESTD.2016.7428776).
[8] IEEE: 802.3bs-2017 (2017) (DOI: 10.1109/IEEESTD.2017.8207825).
[9] 4WDM MSA: http://4wmd-msa.org/.
[10] S. Kanazawa, et al.: “Flip-chip interconnection technique for beyond 100-Gb/s (4 × 25.8-Gb/s) EADFB laser array transmitter,” J. Lightwave Technol. 34 (2016) 296 (DOI: 10.1109/JLT.2015.2462728).
1 Introduction

The ever-growing data capacity of optical-fiber communications systems around data centers is causing an explosive increase of bitrate. The 100G Lambda Multi-Source Agreement (MSA) Group, whose goal is to develop a 4-level pulse-amplitude-modulation (PAM4) based transmission with a 100-G/bit/s (50-Gbaud) per wavelength optical signal, was recently established [1]. At present, the group is focusing on how to realize 100-G/bit/s 2-km, 100-G/bit/s 10-km and 400-G/bit/s 2-km optical links. Unlike in current optical links with rates of 10 or 25 Gbaud, receiver sensitivity degradation owing to chromatic dispersion in single-mode fiber will become a concern in 100-G/bit/s (50-Gbaud) per wavelength PAM4 transmissions, even for the case of a 10-km reach. Moreover, for 400-G/bit/s (4×100-G/bit/s) PAM4 10-km optical links, which have not yet been standardized to our knowledge, the wavelength selection of four wavelength division multiplexing (WDM) will become one of the key points.

A high-speed APD was recently used in a 56-G/bit/s non return to zero (NRZ) 40-km transmission [2] and a 106-G/bit/s PAM4 40-km transmission [3] at a wavelength of 1310 nm, which is close to the zero-dispersion wavelength of the single mode fiber (SMF) used in those experiments. However, it has not been investigated whether such a high-speed APD can keep its high receiver sensitivity characteristics even for conventional SMF with a zero-dispersion wavelength of 1300 to 1324 nm.

In this study, for the purpose of developing a 4×100-Gabit/s PAM4 10-km optical link, we experimentally investigated the chromatic dispersion tolerance of a high-speed APD receiver to a 100-G/bit/s PAM4 signal. To obtain various dispersion conditions, positive or negative dispersion fiber was employed. The chromatic dispersion penalty and minimum receiver sensitivity were better than 1 dB and −11 dBm, respectively, over the dispersion range of 400-Gabit/s 10-km SMF optical link in the conventional LAN-WDM wavelength range.

2 APD receiver

Fig. 1 shows a schematic cross-sectional view of the APD. The APD structure is based on a hybrid absorber combined with the inverted p-down structure we presented previously [4], except a thinner absorption layer of 500-nm to obtain higher bandwidth. The APD chip features a 30-GHz bandwidth and a 2.4-A/W responsivity with a multiplication factor of 3.4 for a 1309-nm wavelength at an optimal bias condition for 100-G/bit/s PAM4 signals.

The chip is mounted on a butterfly-type package together with a single-channel linear transimpedance amplifier with a bandwidth of 32 GHz. The butterfly package has GPPO electrical outputs.

Fig. 2 shows the O/E frequency response of the fabricated single channel APD receiver under an APD bias condition that provides a responsivity of 2.4 A/W for the 1309-nm wavelength. Note that the frequency response includes that of the APD, TIA and electrical interconnections. The 5% smoothed curve is almost flat from zero frequency to 29 GHz, and it rapidly decreases after that towards 50 GHz. The measured 3-dB down bandwidth is 34 GHz, which is almost the same as that of
a 0.7-A/W pin-PD based 100-Gbit/s PAM4 receiver [5, 6]. The measured curve has peaks at 33, 37, and 41 GHz, which might have been caused by the resonance of the butterfly package.

3 Dispersion range and measurement setup

Table I summarizes the wavelength ranges and chromatic dispersion ranges of the existing four-wavelength WDM 10-km optical links based on the IEEE 802.3 Ethernet standards [7, 8] and the 4WDM-MSA [9] specification. There are two major wavelength allocations; one is LAN-WDM with 800 GHz (about 4.5 nm in wavelength) spacing, and the other is CWDM with a 20-nm spacing. To handle the dispersion through the LAN-WDM [A] and CWDM [B] ranges, we employed cut-off shifted SMF (D+) and non-zero dispersion shifted fiber (D−). The D+ fiber has a zero-dispersion slope of 0.105 ps/nm²·km and a zero-dispersion wavelength of 1277 nm, while the D− fiber has 0.0849 ps/nm²·km and 1425 nm. Thus, when using 1310-nm wavelength signals, D+ and D− fiber provide positive and negative dispersion, respectively. In this measurement, we obtained several dispersion conditions by changing the combination of lengths of fiber.
Table 1. Wavelengths and chromatic dispersion ranges of 4λ WDM 10-km optical link

| IEEE standard/MSA specification | Wavelength range | Dispersion range       |
|----------------------------------|------------------|------------------------|
| 100BASE-LR4 (4λ x 25 Gbit/s NRZ) | 1294.53 to 1310.19 nm (800-GHz spacing LAN-WDM grid) | ~28.5 to +9.5 ps/μm |
| 200BASE-LR4 (4λ x 50 Gbit/s PAM4) | 1264.5 to 1337.5 nm (20-nm spacing CWDM grid) | ~28.4 to +9.5 ps/μm |
| 40BASE-LR4 (4λ x 10 Gbit/s NRZ) |                   |                        |
| 4WDM-10 (4λ x 25 Gbit/s NRZ)   |                   |                        |

Fig. 3 shows the setup for evaluating the dispersion tolerance of the 100-Gbit/s PAM4 optical link. A 106-Gbit/s (53-Gbaud) PAM4 electrical signal consisting of a 2^15-1 pseudo-random bit sequence (PRBS) was generated using a 53-Gbit/s NRZ pulse pattern generator (PPG) and PAM4 D/A converter (DAC). The PAM4 optical signal was generated using a 1309.49-nm-wavelength 50-GHz-bandwidth electro-absorption modulator integrated DFB laser (EML) [10] with an average launch power of +4.5 dBm and outer extinction ratio of about 7 dB. Measured chirp parameter (α) was +0.8. On the receiver side, the electrical output signal from the high-speed APD receiver was stored in a 160-GS/s sampling-rate 63-GHz bandwidth real-time digital storage oscilloscope (DSO). Assuming the use of KP4-FEC (RS(544,514)) [7], which has been standardized for use in IEEE 802.3 Ethernet PAM4 links, we defined the receiver sensitivity as the optical input power in optical modulation amplitude (OMA) that provides a pre-FEC bit-error rate (BER) of 2 × 10^-4 when using a variable optical attenuator (VOA). The stored signal was digitally processed offline using a half-symbol-spaced 17-tap feed forward equalizer (FFE); then, the pre-FEC BER was calculated.

![Diagram](image)

Fig. 3. Measurement setup of investigation of dispersion tolerance on 100-Gbit/s PAM4 optical link.

4 Results and discussion

Figs. 4(a) and (b) show the equalized optical eye diagrams and BER curves with the APD receiver after +11.3, 0, and −28.6 ps/μm dispersion fibers. By using the sampling oscilloscope, the eye diagrams were measured using a fiber amplifier with a 30-GHz bandwidth optical plug-in module, and an equalized waveform was
obtained with a built-in symbol-spaced 5-tap FFE. The eye-opening is clear over the entire the dispersion range of $-28.6$ to +11.3 ps/nm, which covers the 10-km reach LAN-WDM [A] in Table I. We could not find any significant degradation in the BER characteristics for the measured dispersion range.

For further investigation of the dispersion tolerance of 100-Gbit/s PAM4 signals, we applied extended dispersion conditions. Fig. 5 shows the minimum receiver sensitivities of the fabricated APD receiver under various dispersion conditions. The receiver sensitivity reaches the best value of $-11.9$ dBm in OMAouter for the zero-dispersion condition, but it abruptly deteriorates as the dispersion increases above +20 ps/nm and decreases below $-40$ ps/nm. We should note again that the dispersion range of a 10-km 400-Gbit/s PAM4 optical link is $-28.4$ to $+9.5$ ps/nm for LAN-WDM [A] (Table I). As shown in Fig. 5, the power penalty caused by chromatic dispersion is less than 1 dB for LAN-WDM [A]. We believe that a 1-dB penalty is allowable in practical use, and the receiver sensitivity is still enough for a four wavelength 400-Gbit/s PAM4 10-km optical link. However, if we assume a CWDM [B] dispersion range of $-59.5$ to +33.5 ps/nm, 10-km transmission would become difficult to realize. Thus, it seems that the LAN-WDM wavelength assignment is favorable for 400-Gbit/s PAM4 10-km optical links.

**Fig. 4.** 100-Gbit/s PAM4 transmission characteristics.
(a) Equalized optical eye diagrams
(b) BER curves with APD receiver
5 Conclusion

We experimentally investigated the impact of chromatic dispersion on a 100-Gbit/s PAM4 optical link. By utilizing a high-speed APD receiver, the chromatic dispersion penalty and the minimum receiver sensitivity was found to be better than 1 dB and −11 dBm, respectively, over a dispersion range of −28.6 to +11.3 ps/nm, which covers the 10-km SMF link in the conventional LAN-WDM wavelength range. This result indicates that the APD-based 400-Gbit/s (4×100-Gbit/s) PAM4 optical link has potential for the 10-km SMF dispersion range.

Acknowledgments

The authors thank Y. Muramoto and T. Ohno for valuable discussions and suggestions. They express their gratitude to K. Maruyama and I. Komiyama for fabricating the receiver and making measurements. The authors are also grateful to S. Kimura and M. Itoh for their continuous encouragement.