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

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Abstract: For the purpose of developing a \(4\lambda \times 100\)-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 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-Gbit/s (50-Gbaud) per wavelength optical signal, was recently established [1]. At present, the group is focusing on how to realize 100-Gbit/s 2-km, 100-Gbit/s 10-km and 400-Gbit/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-Gbit/s (50-Gbaud) per wavelength PAM4 transmissions, even for the case of a 10-km reach. Moreover, for 400-Gbit/s (4λ × 100-Gbit/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-Gbit/s non return to zero (NRZ) 40-km transmission [2] and a 106-Gbit/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 $4\lambda \times 100$-Gbit/s PAM4 10-km optical link, we experimentally investigated the chromatic dispersion tolerance of a high-speed APD receiver to a 100-Gbit/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-Gbit/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-Gbit/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.

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/nm^2·km and a zero-dispersion wavelength of 1277 nm, while the D− fiber has 0.0849 ps/nm^2·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.

![Fig. 1. Schematic cross section of APD structure.](image1)

![Fig. 2. O/E frequency response of fabricated APD receiver.](image2)
Table I. Wavelengths and chromatic dispersion ranges of 4WDM 10-km optical link

<table>
<thead>
<tr>
<th>IEEE standard/MSA specification</th>
<th>Wavelength range</th>
<th>Dispersion range</th>
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<tbody>
<tr>
<td>100GBASE-LR4 (4λ × 25 Gbit/s NRZ)</td>
<td>1294.53 to 1310.19 nm (800-GHz spacing LAN-WDM grid)</td>
<td>−28.5 to +9.5 ps/nm</td>
</tr>
<tr>
<td>200GBASE-LR4 (4λ × 50 Gbit/s PAM4)</td>
<td>1264.5 to 1337.5 nm (20-nm spacing CWDM grid)</td>
<td>−59.5 to +33.5 ps/nm</td>
</tr>
<tr>
<td>40GBASE-LR4 (4λ × 10 Gbit/s NRZ)</td>
<td>1264.5 to 1337.5 nm (20-nm spacing CWDM grid)</td>
<td>−59.5 to +33.5 ps/nm</td>
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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 $2^{31}-1$ 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 $+4.5 \text{ dBm}$ 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 $2 \times 10^{-4}$ 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.

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 $-28.6 \text{ ps/nm}$ 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.
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.

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Fig. 5. Receiver sensitivity versus dispersion for 100-Gbit/s PAM4 signal.