High Linearity and Uniform Characteristics of InP-based 8-CH Waveguide Avalanche Photodiode Array for 400 GbE

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Abstract: InP-based 8-channel waveguide APD arrays were demonstrated towards 400 GbE for the first time. They exhibited maximum 3-dB bandwidth of 23 GHz under high-optical input of –10 dBm and uniformity of avalanche breakdown voltage less than 0.1 V between channels.
OCIS codes: (040.1345) Avalanche photodiodes (APDs); (230.5170) Photodiodes; (130.3120) Integrated optics devices

1. Introduction

To deal with a rapid increase in the internet traffic, 400 Gbit Ethernet (400 GbE) for the transmission of less than 10 km was released in 2017 [1]. For distance from 2 to 10 km, the adoption of 4-level pulse amplitude modulation (PAM4) and 8-channel (CH) wavelength division multiplexing (WDM) systems (Channel rate/λ: 53.12 Gb/s) has been expected, and with respect to transmission distance from 10 to 40 km, discussion is in progress [2]. To construct receiver modules which match with these transmission systems, a high responsivity for long-distance transmission and a wide spectral range for WDM have been demanded for photodiodes. The InP-based avalanche photodiode (APD) which has internal gain through avalanche multiplication is very attractive for 400 GbE, since it has indicated a high responsivity in each band from O to L without additional power consumption [3].

From the viewpoints of receiver modules towards 400 Gb/s and beyond (> 800 Gb/s), the linearity of electrical output against optical signal input for multi-level modulation like PAM4 and uniformity in each characteristic of the APD array with multi channels (number of channel > 8) are enumerated as additional requirements. The nonlinearity of multi-level signals and variation in gain properties between channels bring about excess power consumption and complicated module architecture to compensate them. To overcome these issues, the InP-based waveguide photodiode (WG-PD) array consisting of the butt-joint (BJ) optical coupling structure is very promising. As structural advantages, it has allowed wide bandwidth operation under high optical input power condition while keeping a high responsivity and the uniform properties of the multi-channel WG-PD array [4], [5].

In this paper, we present the InP-based 8-CH WG-APD array for 400 GbE with high linearity and uniform characteristics for the first time. We also demonstrated 53.12 Gb/s (26.56 GBaud) PAM4 operation with the receiver module using fabricated single WG-APD.

2. Device structure and characteristics

Fig. 1 shows the schematic cross-sectional view of WG-APD directly connected with a GaInAsP core waveguide by using the BJ coupling structure. To shorten avalanche build-up time, a thin-film InP multiplication layer thinner than

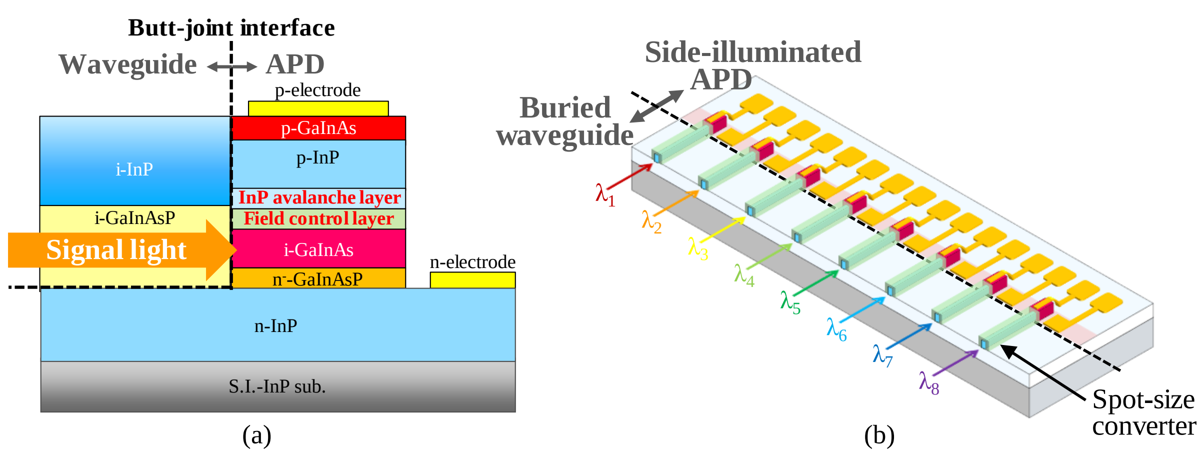


Fig. 1. Schematic diagrams of (a) cross-sectional view of WG-APD and (b) 8-CH WG-APD array.

100 nm was introduced to the APD layer structure. In the WG-PD structure, optical signal was confined in the narrow waveguide core, and the direction of propagation is orthogonal to that of epitaxial growth. Therefore, as compared with the conventional surface-illuminated APD [6], WG-APD yields a small p-n junction area and the thin absorption layer which allow smaller capacitive time constant and shorter carrier transit time while suppressing quantum efficiency penalty. In addition, it enables wide bandwidth operation under high optical input power condition through strong electric field with the introduction of a thinner absorption layer. The fabricated 8-CH APD array is shown in Fig. 1(b). 8 WG-APDs were monolithically integrated on a single chip. The buried waveguide with a spot-size converter and side-illuminated APD structures were formed by regrowth processes.

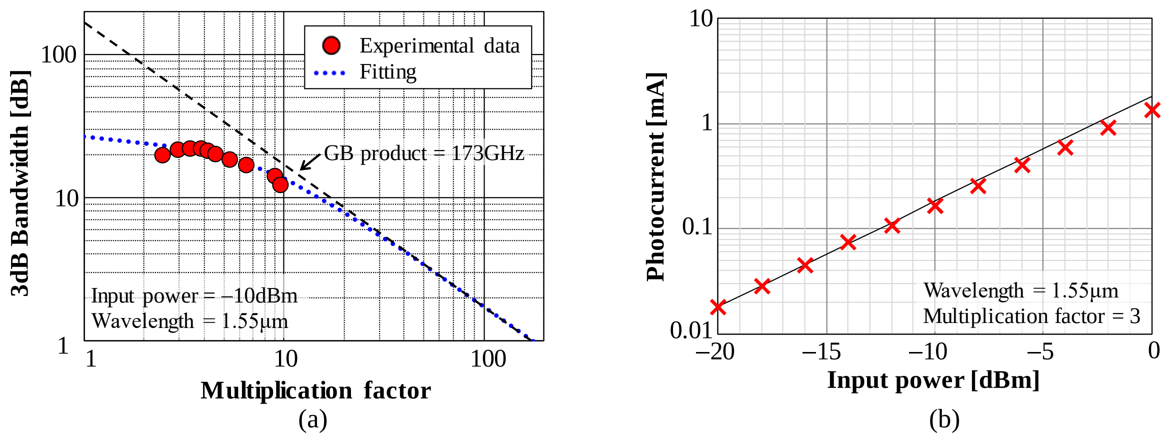


Fig. 2. (a) The multiplication factor versus 3-dB bandwidth: experimental data (circle), multiplication component which is intrinsic avalanche build-up time (dash line) and curve fitting in experimental data (dot line) and (b) input power versus photocurrent of single WG-APD.

Fig. 2 (a) shows the multiplication factor versus 3-dB bandwidth of single WG-APD under optical input power of –10 dBm. The 3-dB bandwidth was more than 16.7 GHz while the multiplication factor was from 2.5 to 6.6. At a multiplication factor of 3.4, we obtained a maximum 3-dB bandwidth of 23 GHz. The multiplication-bandwidth product was estimated to be 173 GHz from intrinsic avalanche build-up time which was extracted by fitting experimental data on a theoretical multiplication factor versus 3-dB bandwidth curve. As shown in Fig. 2 (b), the high linearity of photocurrent was also achieved under optical input power from –20 to 0 dBm at a multiplication factor of 3. The responsivity under the optical input power condition of –10 dBm was only 10 % less than that of –20 dBm. Owing to the WG-APD structure, strong electric field was effectively applied to the thin absorption layer, that is, it contributes to the suppression of non-linear effect including space-charge effect and hetero-barrier trapping. Thus, sufficient 3-dB bandwidth and linearity for 26.56 GBaud PAM4 operation have been successfully achieved.

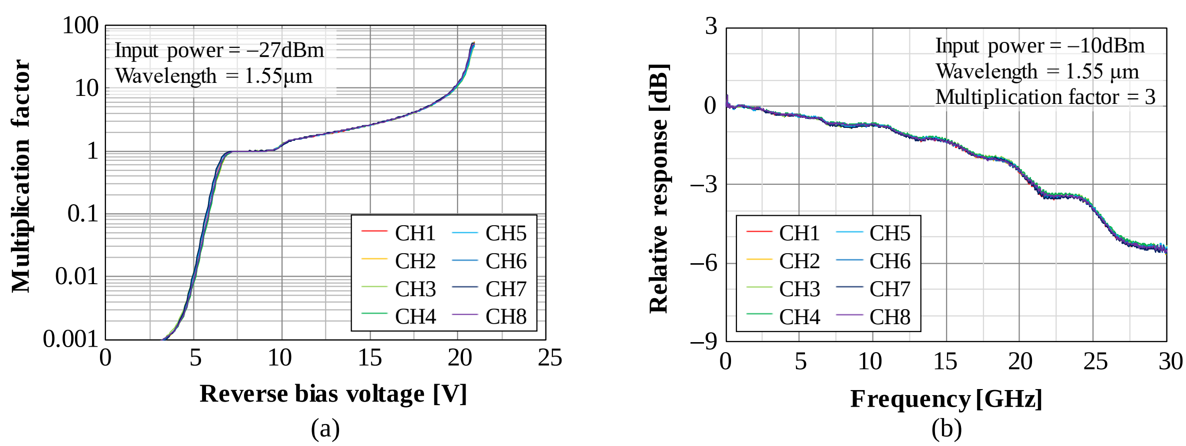


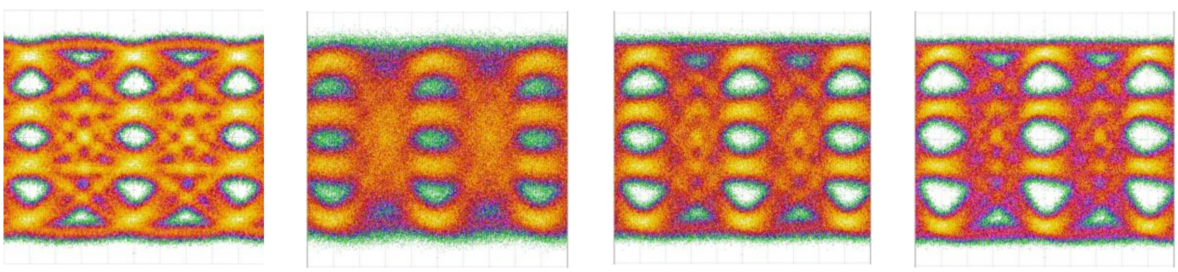
Fig. 3. (a) Multiplication factor versus reverse bias voltage and (b) optical/electrical frequency response in eight channels of WG-APD array

Fig. 3 (a) shows reverse bias voltage dependence on avalanche multiplication characteristics in 8 channels integrated on the WG-APD array. The multiplication characteristics without edge-breakdown and a maximum multiplication factor of more than 50 were observed in all channels. The breakdown voltage was 21 V, and the dark current was less than 5 nA at the 90 % of the breakdown voltage. The responsivity was estimated to be 0.60 A/W from the range of no multiplication at a reverse bias voltage of around 8 V.

Optical/electrical frequency response at a multiplication factor of 3 in 8 channels was shown in Fig. 3 (b). As shown in Fig. 3 (a) and (b), the both curves of the multiplication factor and frequency response almost completely coincided in all of 8 channels. Especially, the variation in avalanche breakdown voltage was only less than 0.1 V. This remarkable uniformity in APD characteristics is derived from the small and thin active region of the WG-APD structure in which the bias voltage to apply certain electric field to the avalanche and absorption layer is very stable. With these results, we propose the receiver module which needs only one DC/DC converter for eight APDs with common bias voltage to realize a simple structure and low power consumption.

3. Performance for 53.12 Gb/s PAM4 operation

A receiver module with single WG-APD and a trans-impedance amplifier (TIA) was assembled to evaluate the performance of 53.12 Gb/s PAM4 operation. A 3-dB bandwidth of the receiver module was more than 20 GHz at a multiplication factor from 3 to 7 under optical input power of –20 dBm. The optical signal was generated by pseudo random bit sequence with the length of 2^{15}-1 (PRBS15Q). Its extinction ratio was 3.8 dB, and transmitter and dispersion eye closure for PAM4 (TDECQ) was 1.55 dB. Fig. 4 shows eye diagrams after back-to-back transmission without equalization under the optical modulation amplitude (OMA) of –14.8, –10.8, and –6.8 dBm at a reverse bias voltage of 19 V as the optimum multiplication factor. The clear eye-opening under the high optical input power condition indicated the sufficient high linearity of WG-APDs.



(a) (b) (c) (d)

Fig. 4. Output waveform without equalization of (a) optical signal and electrical signal of the receiver module with single WG-APD at back-to-back transmission under OMA of (b) –14.8, (c) –10.8 and (d) –6.8 dBm.

4. Conclusion

We realized the InP-based 8-CH WG-APD array consisting of the BJ optical coupling structure for the first time. The sufficient 3-dB bandwidth and linearity for 26.56 GBaud PAM4 operation have been achieved thanks to the WG-APD structure. In addition, extremely uniform characteristics in the 8 channels of the WG-APD array were demonstrated. The receiver module using single WG-APD indicated the high-linearity performance of WG-APDs for 53.12 Gb/s PAM4 operation. From these result, we revealed that the WG-APD array is very promising for 400 GbE and beyond.

5. References

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