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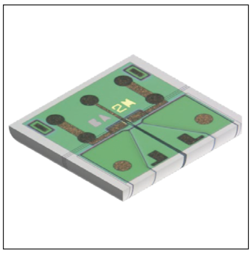

100 GBaud Waveguide Photodetectors for Next-Generation Data Centers

Koji EBIHARA*, Takuya OKIMOTO, Kouichiro YAMAZAKI, Satoru OKAMOTO, Ken ASHIZAWA, and Yoshihiro YONEDA

Optical receivers with intensity-modulation direct detection strongly require ultra-high-speed and high-responsivity performance to 100 GBaud-class toward the next-generation 800 Gbit/s data center networks. This paper demonstrates wide-bandwidth and high-responsivity performance of the InP-based waveguide photodetector integrated with the spot size converter having no polarization dependence. We also introduce the waveguide avalanche photodiodes.

Keywords: intensity modulation/direct detection receiver, waveguide photodetector, polarization-independent spot size converter, 100 GBaud, data center

1. Introduction

Communications traffic is increasing each year owing to the expansion of 5G mobile communication networks and the growth of the video subscription and cloud computing markets. Against this backdrop, optical transmission device interfaces as well as switches and routers that constitute data center (DC) networks are vigorously turning to the 12.8 Tbit/s class of intra-DC communications using 400 Gbit/s optical transceivers. Meanwhile, demand has already risen for additional advances in data transmission speed and capacity. With the aim of enabling either the 25.6 Tbit/s or 51.2 Tbit/s class of intra-DC communications, the 800G Pluggable MSA*[1] group was formed and is exploring the development of 800 Gbit/s optical transceivers (800G Pluggable Transceivers).

Photo 1 shows an example exterior of an 800G Pluggable Transceiver made into the QSFP-DD*[2] form. Receivers consisting of four 200 Gbit/s channels compliant with the FR4 specification*[3] are required to achieve a minimum receiver sensitivity of −6.8 dBm to receive PAM4*[4] signals at a modulation rate of 112 GBaud.*[5] Furthermore, as characteristics of the incorporated photodetector, a 3-dB bandwidth of 60 GHz or higher and responsivity of 0.6 A/W or more are required, necessitating both wide-bandwidth and high-responsivity.

Photodetector structures are generally divided into two types according to the direction of incidence to the optical absorption layer: surface-illuminated and side-illuminated. With the surface-illuminated type, it is easy to achieve high optical coupling efficiency for the absorption layer by forming a large circular photo-detection area; on the other hand, the junction capacitance of photodiodes increases. Thus, surface-illuminated photodetectors are subject to a tradeoff between the 3 dB bandwidth and responsivity characteristics. By contrast, the side-illuminated type receives light perpendicular to the film thickness direction. Therefore, although it is difficult to achieve high optical coupling efficiency for the absorption layer, the designing of the 3 dB bandwidth can be independent from the designing of responsivity because it is possible to make the traveling direction of the produced carrier orthogonal to the direction of incident light. Sumitomo Electric Device Innovations, Inc. has already commercialized a butt-joint coupled waveguide PIN photodiode (PD)[(1),(2)] as a side-illuminated photodetector aimed at both wide-bandwidth and high-responsivity of receivers for coherent communications.*[6]

Figure 1 shows a structural cross section of the butt-joint waveguide PIN PD. The waveguide is integrated into the side-illuminated section using the key technology for

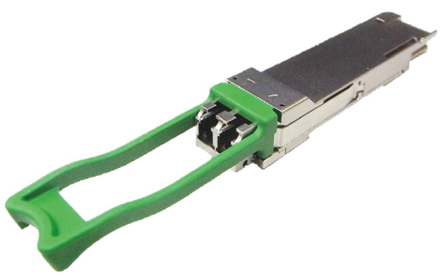

Photo 1. Example exterior of 800G Pluggable Transceiver (QSFP-DD 58.26×18.35×8.5 mm)

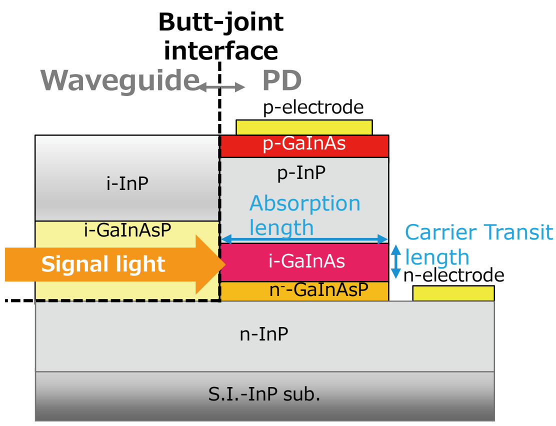

Fig. 1. Structural cross section of butt-joint waveguide PIN PD

InP-based monolithic integration.(3) By directly joining the waveguide core layer to the PD absorption layer, high optical coupling efficiency is realized for the absorption layer, enabling both wide-bandwidth and high- responsivity.

Deploying the butt-joint waveguide PIN PD technology to a photodetector designed for next-generation DCs, we have developed a 100 GBaud waveguide photodetector equipped with wide-bandwidth and high-responsivity characteristics mountable on 800 Gbit/s optical transceivers. This report describes the 100 GBaud waveguide photodetector. Moreover, it also elaborates on its application to avalanche photodiodes (APDs) equipped with photocurrent multiplication.

2. Integration of Polarization-Independent Spot Size Converter

A PD itself is unable to directly detect a modulated signal in a coherent detection system that uses amplitude or phase modulation of an optical carrier. Therefore, it is necessary to place an optically functional waveguide known as a “90° hybrid” that converts and separates a modulated signal into an intensity signal directly detectable by the PD, utilizing the interference between local oscillation light and an optical signal. Thus, the polarization direction of the optical signal is retained and the incident waveguide is designed on the precondition that the polarization direction of the light*7 is constant. By contrast, the intensity modulation/direct detection (IM-DD) system(4) in wide use on DC networks does not retain the polarization direction of the optical signal. Accordingly, the polarization direction of the incident optical signal to the PD fluctuates rather than remaining constant. Figure 2 illustrates the relationships between the form of incidence to the optical absorption layer and polarization directions for the surface-illuminated and side-illuminated types. The surface-illuminated type in (a) receives light by a planar surface; as such, no fluctuation in responsivity characteristics is caused by fluctuation in the polarization direction. On the other hand, the side-illuminated type in (b)—although it is advantageous for achieving both wide-bandwidth and high-responsivity operation—changes in the equivalent refractive index and fluctuates in responsivity in response to fluctuation in the polarization direction. Therefore, to reduce fluctuation in responsivity characteristics caused by fluctuation in the polarization direction, Sumitomo Electric Device Innovations integrated a polarization-independent spot size converter (SSC)*8 into the input waveguide of the waveguide photodetector that uses the IM-DD system for next-generation DCs.

Figure 3 presents the propagation simulation results for the SSC waveguide produced using a three-dimensional beam propagation method. For simplicity in mounting an optical system, the optical mode field diameter was set to 3 µm on the plane of incidence (entrance side) of the SSC waveguide. The mode field on the plane of incidence was formed into a circle to be highly symmetrical. Meanwhile, on the exit side where the light was outgoing to the side of the PD structure, the mode field was formed to match the cross-sectional shape of the PD absorption layer. The transmittance of the SSC waveguide was set to 90% or more and polarization dependence [transverse electric (TE)/transverse magnetic (TM) ratio] was controlled to 1% or less.

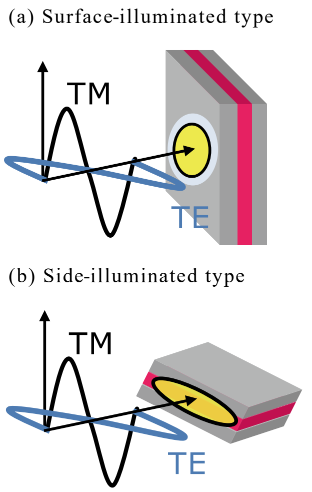

Fig. 2. Relationships between the form of incidence to the optical absorption layer and polarization directions for surface-illuminated and side-illuminated types

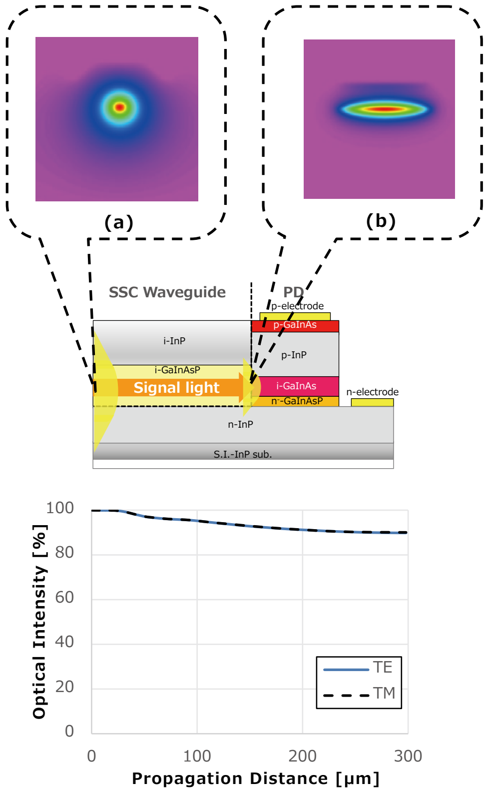

Fig. 3. Optical mode field shapes and optical intensity in the direction of propagation (normalized by the intensity at the entrance) at the entrance (a) and the exit (b) of the SSC waveguide

3. Characteristics of Waveguide Photodetector Integrated with a Polarization-Independent Spot Size Converter

Photo 2 shows a waveguide photodetector integrated with a polarization-independent SSC utilizing a butt-joint regrowth technology. The size of the photodetector was 500 µm × 550 µm to be on a par with previous photodetectors. The arrangement and shape of the electrode pad took into consideration connectivity with the following transimpedance amplifier (TIA)[*9]-IC. The electrode pad was built into a pillar structure to be compatible with flip-chip mounting.[*10]

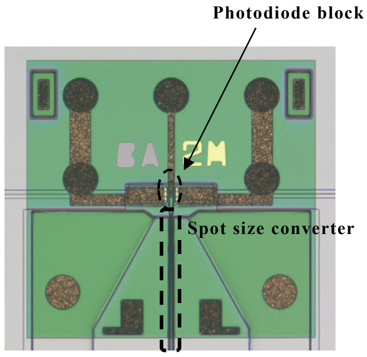

Photo 2. 100 GBaud waveguide photodetector

Figure 4 plots the polarization dependence of the responsivity of the newly fabricated waveguide photodetector. Its fluctuation in responsivity caused by polarization was controlled to 1% or less, with the responsivity being 0.77 A/W or more. Furthermore, Fig. 5 plots the frequency characteristics of the waveguide photodetector. It achieved the 3 dB bandwidth at 60 GHz or higher owing to reduced PIN PD junction capacitance and shortened travel time of the produced carrier. The waveguide photodetector proved itself to be able to achieve wide-bandwidth and high responsivity characteristics.

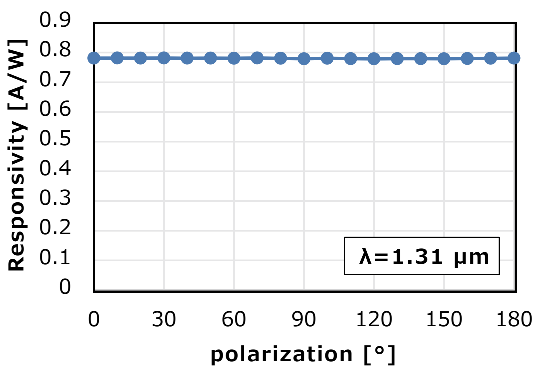

Fig. 4. Polarization dependence of waveguide photodetector

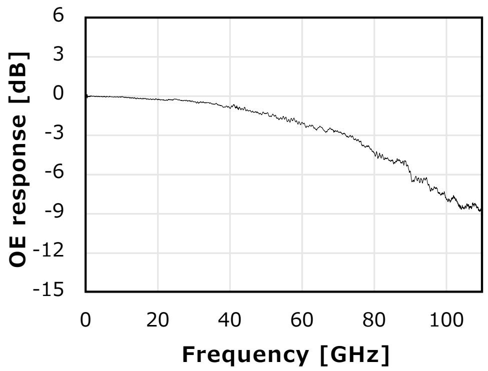

Fig. 5. Frequency characteristics of waveguide photodetector

4. Application to Avalanche Photodiodes (APDs)

PIN PDs are unable to exhibit adequate responsivity for transmission distances of 10 km or more. To deal with this challenge, expectations are high for APDs capable of photocurrent multiplication from the perspective of power consumption reduction. A waveguide photodetector (APD) has been created by applying the butt-joint waveguide PIN PD technology, which is advantageous in terms of high linearity as well as wide-bandwidth operation.(5) Figure 6 shows a structural cross section of the waveguide photodetector (APD).

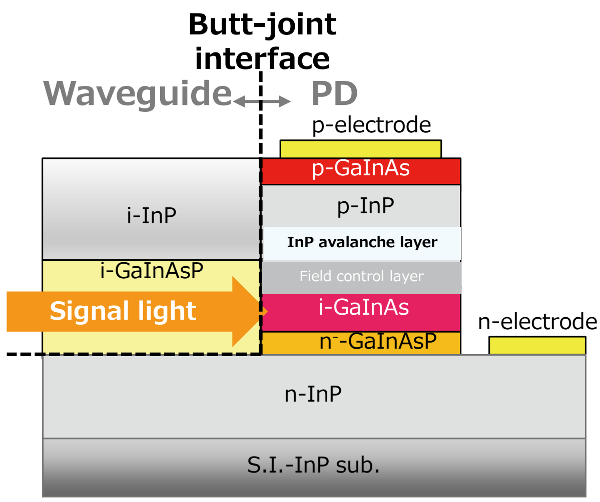

Fig. 6. Structure of butt-joint waveguide photodetector (APD)

Using the butt-joint regrowth process of the constituent technology for InP-based monolithic integration, an incident waveguide incorporating i-GaInAsP as the core layer and an APD with an InP multiplication layer (100 nm or less in thickness) were integrated into a monolithic form. The structure in which the APD absorption layer (i-GaInAs) is directly coupled to the cross section of the waveguide core layer demonstrates high quantum efficiency in the absorption layer and high-speed performance due to the wide CR bandwidth of the downsized p-n junction region and reduced carrier transit time in the thin absorption layer. Under conditions of high electric field and high input power, a high linear responsivity is obtained by avoiding space charge effects and trapping effects at the hetero junction in the thin absorption layer. Figures 7 and 8 plot the dark current characteristics and multiplication characteristics at a wavelength of 1.31 µm, respectively, of the waveguide photodetector (APD). Its breakdown voltage was 21.6 V. In addition, the waveguide photodetector (APD) exhibited low dark current characteristics of 5 nA or less at the 90% value of the breakdown voltage. We demonstrated the responsivity is 0.70A/W at a multiplication factor of 1, and the maximum multiplication factor is 20 without edge breakdowns.

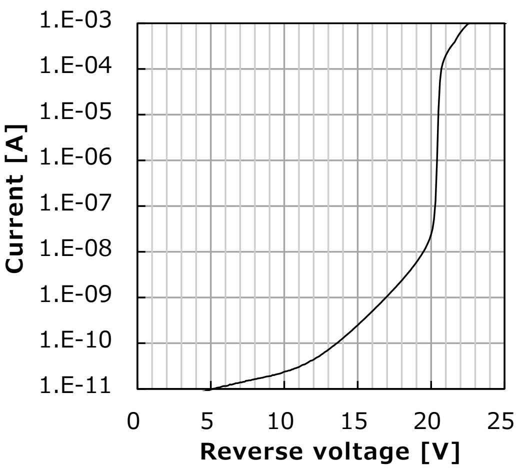

Fig. 7. Dark current characteristics of waveguide photodetector (APD)

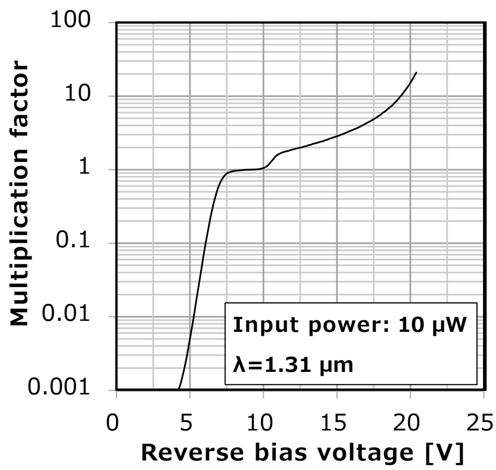

Fig. 8. Multiplication characteristics of waveguide photodetector (APD)

5. Conclusion

We have successfully achieved both the PD band (> 60 GHz) and responsivity (> 0.7 A/W) required for 100 GBaud receivers. This success was made possible by the integration of a polarization-independent spot size converter, essential for direct detection, being based on a waveguide PIN PD technology, with the PD incorporating a butt-joint structure commercialized for coherent communication receivers. In addition, this report described application of the waveguide photodetector to APDs capable of photocurrent multiplication.

Technical Terms

*1 800G Pluggable MSA: In September 2019, 10 development vendors formed the multi-source agreement (MSA) group. They established the agreement to standardize optical transceiver specifications for next-generation data center communications with the aim of developing and commercializing compatible products manufactured to common specifications.

*2 QSFP-DD: Quad Small Form Factor Pluggable Double Density: One of the industrial standards for pluggable optical transceivers. QSFP-DD achieves 800 Gbit/s by using four-wavelength optical signals at a transmission rate of 200 Gbit/s.

*3 FR4 specification: The standard specification for optical transceivers within 2 km reach; FR4 is intended for wavelength-division multiplexing for transmission using four-wavelength optical signals.

*4 PAM4: Four-level pulse amplitude modulation that can transmit two-bit information per symbol.

*5 Baud: A unit of modulation rate; the number of carrier modulation cycles per second.

*6 Coherent communication: A communication scheme used to transmit signals by modulating optical amplitude (intensity) and phase; normally, two types of fixed polarized light are used for transmission.

*7 Polarization direction of light: The direction in which the electric field (magnetic field) of light oscillates; a wave is called a transverse electric (TE) wave if in its polarization direction the electric field component is transverse with respect to the plane of incidence, while it is called a transverse magnetic (TM) wave if in its polarization direction the magnetic field component is transverse with respect to the plane of incidence.

*8 Spot size converter: A waveguide structure that converts light beam diameters.

*9 Transimpedance amplifier (TIA): An amplifier that converts the received photocurrent to a voltage; TIAs are placed to follow a photodetector.

*10 Flip-chip mounting: A way of mounting semiconductor chips in which the semiconductor chip is connected to external circuits with its top and bottom inverted.

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Contributors

The lead author is indicated by an asterisk (*).

K. EBIHARA*
• Sumitomo Electric Device Innovations, Inc.

T. OKIMOTO
• Transmission Device Laboratory

K. YAMAZAKI
• Sumitomo Electric Device Innovations, Inc.

S. OKAMOTO
• Sumitomo Electric Device Innovations, Inc.

K. ASHIZAWA
• Assistant Manager, Sumitomo Electric Device Innovations, Inc.

Y. YONEDA
• Senior Assistant General Manager, Sumitomo Electric Device Innovations, Inc.