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InP-based Photodiodes Integrated with Optical Mixer for 800 Gbit/s Coherent Transmission

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Due to the rapid growth of internet traffic, the transmission capacity of optical coherent communication is about to reach 800 Gbit/s. Photodetectors for coherent receivers are required to have three key features: wide frequency bandwidth to support 100 GBaud operations, high responsivity to mitigate the power consumption of local oscillators, and multifunctional integration to reduce footprint and cost. We have developed a wide-bandwidth and high-sensitivity InP-based optical mixer-integrated photodetector that can be installed in an 800 Gbit/s coherent receiver, and a multifunctional integrated photodetector that enables the downsizing and cost reduction of coherent receivers.

Keywords: 800 Gbps, coherent receiver, IC-TROSA, 90° hybrid, InP monolithic integration

1. Introduction

Society is undergoing a transformation with high-capacity data transmission via the internet at the foundation. For instance, the commencement of 5G services enables the transmission of high-resolution video and the proliferation of telework permits people to work with fewer locational restrictions. This transformation is supported by fiber-optic communications technology. The biggest challenge facing it is how to fulfill the demand for ever-increasing network traffic.

Digital coherent transmission systems that utilize phase-shift modulation are suited to high-capacity, long-haul communications. Hence, they are in wide use, from backbone network connecting large cities via optical submarine cables to interurban metro area networks, and to data center interconnect (DCI) networks. Presently, in 2021, 400 Gbit/s coherent transmission systems are increasingly appearing on the market. In response to growing market demand, discussions have already begun on standardizing coherent transmission systems up to 800 Gbit/s.[1]

Three essential requirements should be fulfilled by coherent optical receivers (or coherent receivers) for 800 Gbit/s transmission, which are an increased symbol rate, reduced power consumption, and a downsized, low-cost module. Photodetectors used in the coherent receiver should come with wide bandwidth supporting high symbol rates of up to 100 Gbaud. Moreover, the photodetector must also meet the strong demand for high responsivity and multifunctional integration. High responsivity reduces the local oscillator load, which otherwise results in increased power consumption, and multifunctional integration shrinks footprint and cost.

Sumitomo Electric Industries, Ltd. has developed a 400 Gbit/s coherent receiver[2] and InP-based photodiodes (PDs) integrated with an optical mixer[3] designed as a photodetector, both of which exhibit favorable characteristics. The company has recently developed an InP-based PD array integrated with optical mixer exhibiting wide-bandwidth and high-responsivity characteristics suitable for 800 Gbit/s coherent receivers. The company has also developed a multifunctional integrated photodetector useful for module miniaturization and cost reduction. This report presents the development results.

2. Configuration of the Coherent Receiver

Photo 1 shows the exterior of the coherent receiver. The package is 12.0 × 22.7 × 4.5 mm in size and compliant with OIF*1 Implementation Agreement for Type 1 Micro-ICR.[4] Coherent transmission uses a system of multiplexing with two polarizations (X and Y) of optical signals phase-shift modulated by quadrature phase-shift keying (QPSK)*2 or other schemes. The coherent receiver separates these signals into polarized components and decodes the optical phase signals into voltage signals.

Figure 1 illustrates the internal structure of the coherent receiver. First, the polarizing beam splitter (PBS) separates input signal beams into X and Y polarized components. The Y polarized component is converted into an X polarized light by the half-wave plate (HWP). Part of

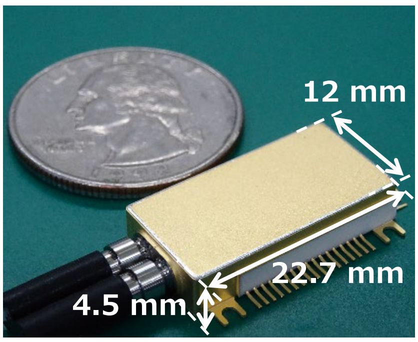

Photo 1. Exterior of coherent receiver

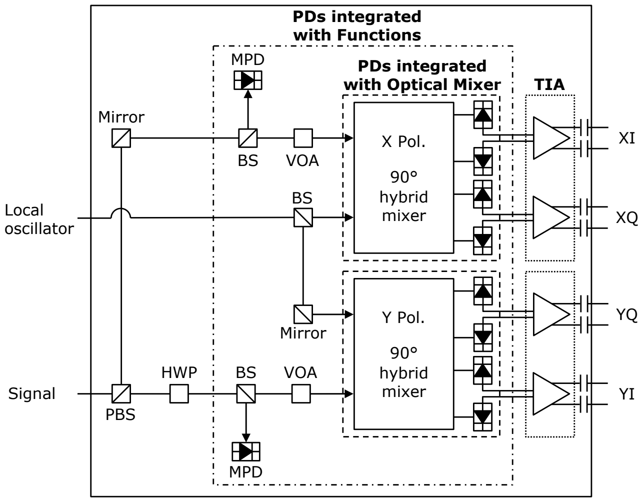

Fig. 1. Internal structure of coherent receiver

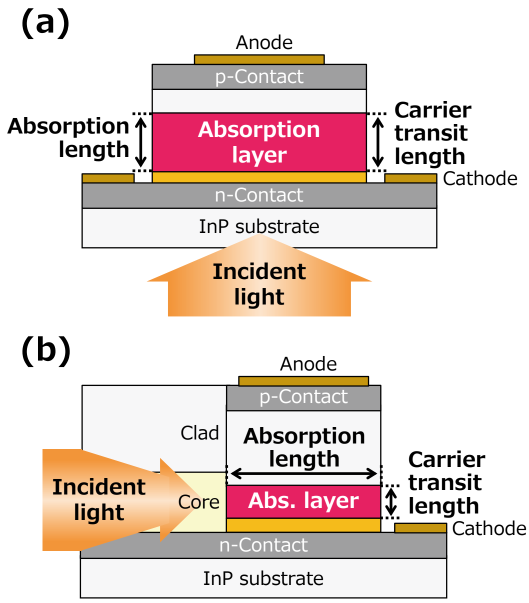

Fig. 2. Schematic structural diagrams of
(a) surface-illuminated PD and (b) waveguide PD

each of the two signals is directed to the monitor PD (MPD) by the beam splitter (BS). The remaining part of the optical signals are power-adjusted through the variable optical attenuator (VOA). Subsequently, the optical signals are inputted to 90° hybrid optical mixers*3 assigned to X and Y polarization. Phase signals are converted into intensity signals through interference with local oscillator light inputted through a separate path to the 90° hybrid optical mixer. Signal components are respectively inputted to PDs assigned to four channels. In this process, the higher responsivity of PDs contributes to lower power used by the local oscillator, hence lower power consumption by the coherent receiver. Signals converted by the PDs into current signals are converted into voltage signals and amplified by the trans-impedance amplifier (TIA) and output from the receiver.

The performance of a coherent receiver is indicated by its bandwidth and responsivity, which greatly depend on the performance of the photodetectors. Sumitomo Electric has been employing InP-based waveguide PDs in coherent receivers for wide-bandwidth operation, high responsivity, and module miniaturization.

Figure 2 presents schematic diagrams of a commonly used surface-illuminated PD and the waveguide PD manufactured by Sumitomo Electric. The bandwidth and responsivity of a PD are limited by its carrier transit length and absorption length. Shorter carrier transit lengths contribute to faster transport of photo-generated carriers, and therefore to improved bandwidth. Meanwhile, longer absorption lengths mean absorption of a larger amount of light for carrier generation, contributing to improved responsivity. The surface-illuminated PD is structured so as to have incident light orthogonal to the absorption layer, as shown in Fig. 2 (a). Consequently, its carrier transit length equals its absorption length. Accordingly, there is a fundamental trade-off between the bandwidth and the responsivity of the surface-illuminated PD. In contrast, the waveguide PD has a structure in which incident light comes parallel to the absorption layer, as illustrated in Fig. 2 (b). This structure enables the carrier transit length and absorption length to be designed independently. This means that it is possible to achieve both wide-bandwidth operation and high responsivity by designing a thin and long absorption layer—or by extending the absorption length while preserving a short carrier transit length—to the extent that no degradation occurs in terms of bandwidth, attributable to increased electrical capacitance.

Moreover, using Sumitomo Electric's InP-based monolithic integration technology, it is possible to integrate the waveguide PDs with an optical mixer and various other waveguide devices into one chip. This integration is very helpful for module miniaturization and cost reduction through the use of fewer installed optical components and a smaller footprint for the coherent receiver. In addition, Sumitomo Electric has used a butt-joint regrowth technique(5) to develop a structure in which the output waveguide core of a 90° hybrid optical mixer is directly connected to the absorption layer of the waveguide PD. This structure is intended to achieve high optical coupling efficiency for even higher responsivity.

3. Designing 800G Photodetector

Photo 2 shows the exterior of an InP-based PD array integrated with a 90° hybrid optical mixer. Figure 3 is its structural diagram. The integrated photodetector is a miniature chip 1.6 mm wide, 4.1 mm long, and 0.1 mm thick. Using the butt-joint regrowth technique, this single chip integrates a 90° hybrid optical mixer and PDs assigned to four channels.

The 90° hybrid optical mixer consists of InP-based optical waveguides which have a core made of a high-refractive-index GaInAsP material. It is comprised of three elements: 2 × 4 MMI*4, 45° phase shifter, and 2 × 2 MMI. Spot-size converters (SSCs)*5 are integrated at the input ports of the optical mixer. SSCs ensure adequate mounting tolerances for assembling the coherent receiver and also

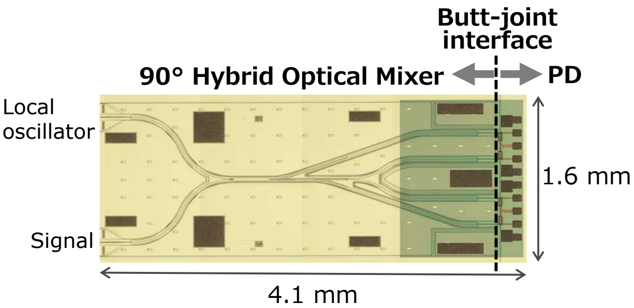

Photo 2. Exterior of InP-based PD array integrated with a 90° hybrid optical mixer

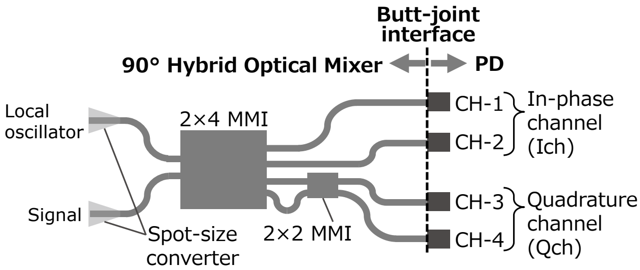

Fig. 3. Structural diagram of InP-based PD array integrated with a 90° hybrid optical mixer

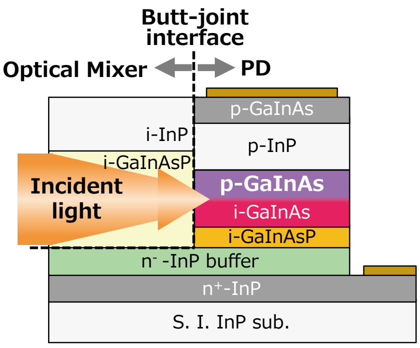

Fig. 4. Cross section of 800G photodetector

high coupling efficiency between the lens and the optical mixer.

Figure 4 shows a cross section observed at the butt-joint interface between the 90° hybrid optical mixer and PDs. Sumitomo Electric has introduced three structures to achieve a wide-bandwidth and high-responsivity photodetector that can be installed in an 800 Gbit/s coherent receiver. The first is a low-concentration n-type InP buffer layer(3) placed immediately beneath the absorption layer on the PD side and the core layer on the optical mixer side. On the PD side, the buffer layer contributes to wide-bandwidth operation by broadening the depletion layer for reduced electrical capacitance; on the optical mixer side, it prevents decreases in responsivity by separating the core from the high-concentration n-type InP contact layer for suppression of free carrier absorption*6. The second is the i-type GaInAsP buffer layer(6) inserted between the absorption layer and the low-concentration n-type InP buffer layer. For wide-bandwidth operations capable of 800 Gbit/s transmission, it is necessary to design an absorption layer thinner than the core layer for a short carrier transit length. However, this raises concern about lower optical coupling efficiency due to a mismatch in light intensity distribution at the butt-joint regrowth interface. To address this concern, Sumitomo Electric used the i-type GaInAsP buffer layer so as to ensure that the centers of the core layer and the absorption layer are positioned at equal elevation for elimination of the mismatch in light intensity distribution at the butt-joint regrowth interface. Consequently, high responsivity was attained despite the use of a thin absorption layer required for 800 Gbit/s transmission. The third is a dual-layer absorber that combines a p-type GaInAs absorption layer and i-type GaInAs absorption layer. Compared with the i-type, p-type doped GaInAs absorption layers are free of the need to consider the transit of holes working as the majority carrier, although the p-type generates slightly fewer carriers. Therefore, it becomes possible to reduce the effective transit length of holes without altering the overall thickness of the absorption layer, enabling even wider bandwidth operation with the high responsivity intact.

4. Evaluation for 800G Photodetector

This chapter presents the evaluation results for the photodetector for 800 Gbit/s transmission fabricated by Sumitomo Electric.(7) Figure 5 plots the optical / electrical frequency response characteristics of the four PDs integrated in the device. All four channels achieve 3 dB bandwidth of 65 GHz or higher to support a 100 Gbaud symbol rate. This is attributable to the reduced electrical capacitance made possible by the low-concentration n-type InP buffer layer and the shortened transit length of holes due to the dual-layer absorber. Figure 6 plots the spectral responsivity of the four channels in the C-band wavelength range. The responsivity contains optical coupling loss in SSC, intrinsic loss in the 90° hybrid optical mixer, excess loss in the waveguide, and optical coupling loss at the butt-joint regrowth interface. The average responsivity of the four channels reached 0.155 A/W at a wavelength of 1550 nm at the center of the C band. This achievement was brought about by the high optical coupling efficiency due to SSC

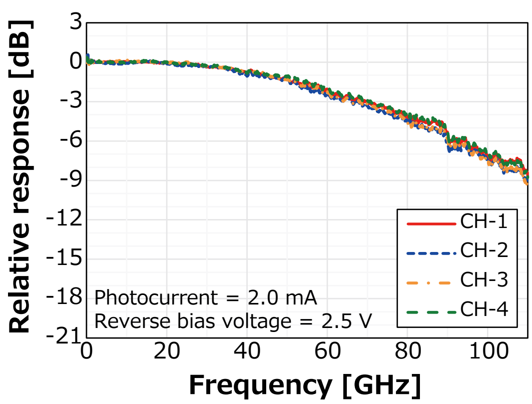

Fig. 5. Frequency responses of InP-based PD array integrated with a 90° hybrid optical mixer

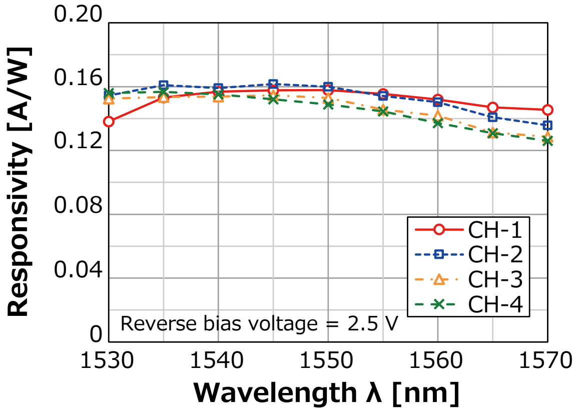

Fig. 6. Responsivity of InP-based PD array integrated with a 90° hybrid optical mixer

integration, reduced optical loss in the waveguide of the 90° hybrid optical mixer attributable to the insertion of the low-concentration n-type InP buffer layer, and high optical coupling efficiency at the butt-joint regrowth interface due to the introduction of the i-type GaInAs buffer layer.

Thus, the above-described results, brought about through the introduction of the three structures detailed in the preceding chapter, demonstrate that the InP-based PD array integrated with a 90° hybrid optical mixer comes with both wide-bandwidth operation and the high responsivity required of 800 Gbit/s transmission.

5. Multifunctional Integrated Photodetector

Using an InP-based monolithic integration technology, Sumitomo Electric fabricated a multifunctional integrated device, which is a single device integrating the functions of components previously provided as discrete components, with the aim of enabling module miniaturization and cost reduction for coherent receivers.(7)

Photo 3 shows the exterior of the fabricated device. It is a single chip 4.1 mm in length and 2.6 mm in width, which integrates as many as 19 functions. The device described in the preceding chapter only integrated one 90° hybrid optical mixer and four PDs, necessitating two units of the device to be incorporated in a module to handle two polarized components. In contrast, a single unit of the multifunctional integrated photodetector integrates two 90° hybrid optical mixers and eight PDs. Consequently, only one device is required to be installed in a module. Furthermore, it integrates two MPDs, two VOAs, and three BSs, which have previously been installed as discrete components. The reduced number of components installed is substantial in terms of component material and assembly cost reductions and module miniaturization. The VOA employs a Mach-Zehnder interferometer structure and is driven by virtue of a thermo-optic effect from a heater formed on the waveguide. Its maximum extinction ratio is −28 dB with its power consumption being 68 mW at this extinction ratio.

The multifunctional integrated photodetector fabricated by Sumitomo Electric has PDs assigned to eight channels, which exhibit reverse bias I-V characteristics, as shown in Fig. 7. Figure 8 presents its wavelength dependence of channel imbalances. Owing to the InP-based monolithic integration technology owned by Sumitomo Electric, the multifunctional integrated photodetector with its high degree of perfection compares favorably with the integrated photodetector described in the preceding chapter. In terms of characteristics, the multifunctional one has almost completely uniform I-V characteristics over eight channels and channel imbalances of no more than ±0.3 dB throughout the C-band.

The multifunctional device is of course effective in reducing the size and cost of coherent receivers. Moreover,

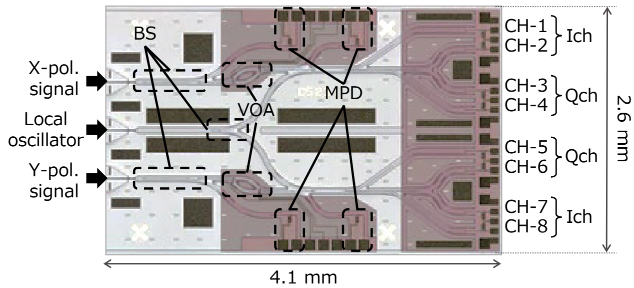

Photo 3. Exterior of multifunctional integrated photodetector

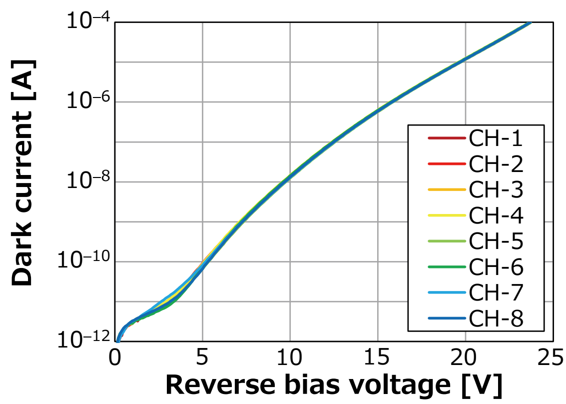

Fig. 7. Reverse bias I-V characteristics of multifunctional integrated photodetector

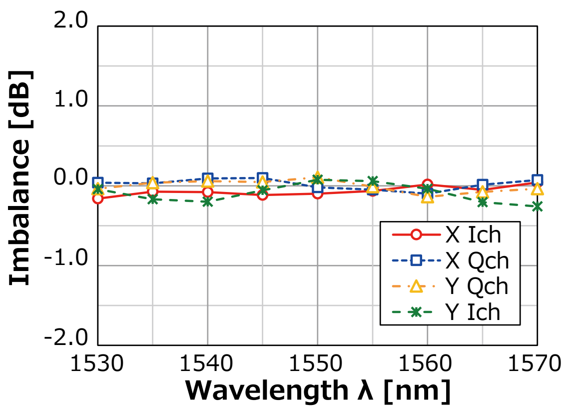

Fig. 8. Channel imbalances of multifunctional integrated

it is promising as a device for installing in IC-TROSA*7, which is a combination transmitter/receiver module that needs to meet the demand for additional miniaturization and cost reduction.

6. Conclusion

Sumitomo Electric developed an InP-based photodetector integrating a 90° hybrid optical mixer and waveguide PDs into a single device. By introducing three structures, it had success in achieving both wide-bandwidth operation supporting a 100 Gbaud symbol rate and high responsivity contributing to reduced local oscillator power. Furthermore, using an InP-based monolithic integration technology, Sumitomo Electric proved a multifunctional integrated photodetector integrating as many as 19 functions into a single chip 4.1 mm in length and 2.6 mm in width. This device fulfills the requirements for wide-bandwidth operation and the high responsivity required of 800 Gbit/s coherent receivers and, at the same time, helps to achieve module miniaturization and cost reduction. These devices will with certainty contribute greatly to the building of large-capacity optical communication networks essential for the future society.

Technical Terms

*1 OIF: Optical Internetworking Forum: An industrial consortium formed to promote optical network technologies and standardization.

*2 Quadrature phase-shift keying (QPSK): A phase-shift modulation scheme that assigns two-bit data to four phases shifted at 90° intervals. In QPSK, each bit is grouped into in-phase and quadrature components.

*3 90° hybrid optical mixer: A mechanism designed to output in-phase and quadrature components by allowing local oscillator light to interfere with signal light within a coherent receiver.

*4 MMI: Multi-mode interference: A waveguide structure designed to distribute light utilizing multi-mode interference occurring in the waveguide.

*5 Spot-size converter (SSC): A waveguide structure that comes with the capability to convert the beam diameter of light.

*6 Free carrier absorption: Optical absorption occurring in metal or high-concentration-doped semiconductors. Free carrier absorption occurring in an optical mixer results in optical loss, and in turn causes reduced responsivity.

*7 IC-TROSA: Integrated coherent transmit-receive optical sub-assembly: A coherent communication module with integrated transmitter and receiver functions.

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