

InP/Si Heterogeneous Integration Platform Using Chip-on-Wafer Bonding Technology

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With the development of various IoT applications and AI technologies, data traffic has been rapidly increasing. The data rate required for a single transceiver is expected to reach the 10 Tb/s class in 2030. On the other hand, single-material photonic devices that support optical communication systems are beginning to show limitations in simultaneously achieving high bandwidth and low power consumption for multi-Tb/s-class data transmission, necessitating a technological breakthrough. Heterogeneously integrated photonic devices combine the advantages of two key technologies. First, III-V compound semiconductors, which provide high-speed and high-efficiency operation. Second, silicon photonics, which enables high-density integration through device miniaturization. By leveraging both advantages, these devices make a promising approach to overcome the inherent limitations. In this paper, we introduce heterogeneous integration technology using a chip-on-wafer bonding process. We also report on wavelength-tunable lasers, Mach-Zehnder modulators, and photodetectors utilizing the benefits of heterogeneous integration.

Keywords: heterogeneous integration, InP, silicon photonics, chip-on-wafer bonding

1. Introduction

The mobile systems, such as the fifth generation mobile communications system (5G) and the sixth one (6G), have advanced, and it has accelerated the evolution of Internet of Things (IoT) applications in which various things are connected to the Internet. In addition, artificial intelligence (AI) technology, including ChatGPT, has rapidly come into widespread use, significantly improving convenience in people's lives with these developments. Along with these trends, for AI data center networks, distributed AI data centers (scale-across), which improve their processing capacity by using a graphics processing unit (GPU) cluster through setting up multiple data centers, are proposed, in addition to the advancement of scale-up (connecting between GPUs) and scale-out (between servers). Accordingly, the additional development of AI technology is anticipated. In this context, fiber-optic communication, which is the mainstay of communication networks, is facing the need to offer high-speed and high-capacity capabilities for short-reach transmission—as exemplified by access networks and data center networks—and for metropolitan-areas to long-haul transmission as well. Moreover, as demand for optical transceivers that perform data transmission is growing rapidly, photonic devices installed in them are facing the strong need to offer both high-speed operation and low-power consumption. Along with the expanding data transmission capacity as described above, a data rate that optical transceivers are required to achieve is expected to reach the 10 Tb/s class by 2030.

To date, optical communication systems have used photonic integrated devices utilizing indium phosphide (InP)⁽¹⁾, which is a III-V compound semiconductor,^{*1} and silicon (Si) photonics.^{*2,(2)} Since, towards 10 Tb/s class data transmission, photonic devices fabricated using a single material with InP or Si photonics have a limitation for high-speed operation, it has been considered that one

promising approach would be to expand the transmission capacity by setting up a multi-channel configuration comprising the above-mentioned devices with the single material. However, concerns about this approach include an increased device size, increased cost, and greater power consumption due to parallel processing. For example, even in the case of small and low-power consumption optical transceivers designed for digital coherent transmission^{*3} being compatible with an 800 Gb/s transmission rate, 12 channels or more would be required to achieve 10 Tb/s class transmission, resulting in the total power consumption exceeding 200 W. Hence, drastic approaches would be required to reduce devices' power consumption. Thus, single-material photonic devices, which have supported conventional optical communication systems, are approaching their limitations in terms of both high-speed operation and low power consumption, thereby calling for a technological breakthrough.

Expectations are high for heterogeneous integration-based photonic device technology that leverages their respective advantages of III-V compound semiconductors and Si photonics—to place the appropriate materials in the appropriate places—as a promising approach towards overcoming characteristic limitations on single-material photonic devices. Single-material photonic devices principally use III-V compound semiconductors, such as InP-based materials, which are excellent for achieving high-speed and high-efficiency operation. By placing III-V compound semiconductors on an advantageously low-cost and high-density integration-capable Si photonics platform, it is possible to produce compact photonic integrated circuits capable of high-speed operation. Furthermore, designs leveraging their respective advantages are expected to achieve more efficient and lower power-dissipating operation than that of single-material photonic devices.^{(3),(4)} This paper describes heterogeneous integration technology, which is the process of directly bonding InP chips onto a

Si-on-insulator (SOI) wafer, and reports on a wavelength-tunable laser, Mach-Zehnder (MZ) modulator, and photodetector fabricated using the process.

2. InP Chip-on-SOI Wafer Bonding

Numerous investigations have been reported on heterogeneous-integration approaches combining III-V compound semiconductors and Si photonics. Methods which have been in frequent use are as follows: an integration technique that achieves butt joints at the facets of both materials when assembled,⁽⁵⁾ micro-transfer printing, which picks up devices fabricated on a III-V compound semiconductor wafer, and bonds them at a desired location on a Si photonics wafer,⁽⁶⁾ and direct bonding, which produces an integrated device by bonding a wafer or chips of a III-V compound semiconductor onto a Si photonics wafer, followed by processing in the region of the III-V compound semiconductor.^{(7),(8)} Against this backdrop, we have studied heterogeneously integrated photonic devices by means of InP chip-on-SOI wafer bonding. This heterogeneous integration technology enables the integration of various functions at high density into a single Si photonic integrated chip through the bonding for different types of III-V compound semiconductor chips. Furthermore, it offers much better alignment accuracy between InP-based active regions and Si waveguides compared with other methods by leveraging the highly accurate alignment of a stepper lithography process after bonding. Due to its high positioning accuracy, this technique minimizes optical coupling loss caused by the deviation of waveguide positions between InP and Si, thereby attaining high optical coupling efficiency between InP and Si waveguides.⁽⁹⁾ It is considered that this feature is advantageous in terms of multi-functional integration of InP-based active regions on Si photonic circuits.

Figure 1 illustrates the process flow followed for InP chip-on-SOI wafer bonding.⁽⁸⁾ The first step is to prepare an InP wafer with a desired epitaxial structure grown through the organometallic vapor-phase epitaxy, which is then divided into InP chips. After division, the InP chips undergo ultrasonic cleaning to remove foreign matter from the surface. The next step is to expose the surfaces of the InP chips to ultraviolet (UV) rays and ozone in order to make their surfaces hydrophilic. A contact angle measurement has shown that the UV-ozone-treated surface has become satisfactorily hydrophilic. Surface-treated InP chips are then bonded at desired positions on an SOI wafer through the pick-and-place technique. Process steps up to this point are taken under atmospheric pressure. The next step is to anneal them under a load at a temperature of 150°C in a vacuum chamber. Annealing accelerates dehydration condensation at the bonding interface and produces the strong bonding state via an oxidized layer. Figure 2 shows the photomicrograph of an SOI wafer after the bonding of InP chips, which depicts InP chips bonded with high density onto Si photonic circuits.

Using the above-described chip bonding process, we verified the feasibility of multi-functional integration of InP-based active devices.⁽¹⁰⁾ Si photonic circuits that functionally modeled a coherent transceiver were fabricated,

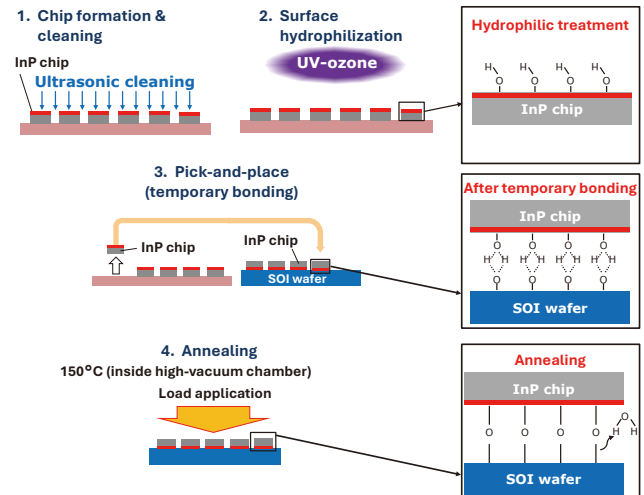


Fig. 1. Process flow of InP chip-on-SOI wafer bonding

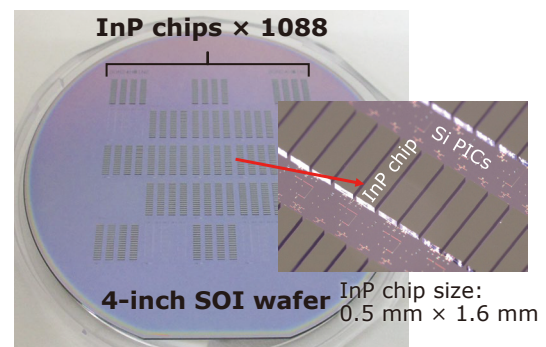


Fig. 2. Photomicrograph of SOI wafer after bonding process of InP chips

and 21 InP chips (chip size: 0.5 mm × 1.6 mm) with differently configured epitaxial layers were bonded within an 8.8 mm × 6.0 mm region on the wafer of the Si photonic circuits, and an evaluation was conducted. This investigation used three types of InP chips designed for lasers with the same structure as semiconductor optical amplifiers (SOAs), modulators, and photodetectors. Figure 3 shows a photomicrograph after bonding.⁽¹⁰⁾ It was verified that each InP chip was bonded at each desired location. Furthermore, after bonding, the InP substrate was removed by wet-chemical etching to leave the epitaxial layer alone on the Si photonic circuits. From the observation of the surfaces, it was revealed that the three types of epitaxial layers with different thicknesses were bonded onto the Si photonic circuits without peeling off in each InP chip. The photoluminescence spectra of these InP chips were measured. These spectra had peak intensity at the wavelengths of 1,200 nm, 1,530 nm, and 1,610 nm, which agree with light emitted from the GaInAsP core layer of the modulator, the GaInAsP active layer of the laser and SOA, and the GaInAs absorber of the photodetector, respectively. These results prove that the chip-on-wafer (CoW) bonding technology is valid for the bonding of InP chips with different thicknesses and different epitaxial layer compositions at desired locations on Si photonic circuits and is very promising for achieving multi-functional and high-density integration of

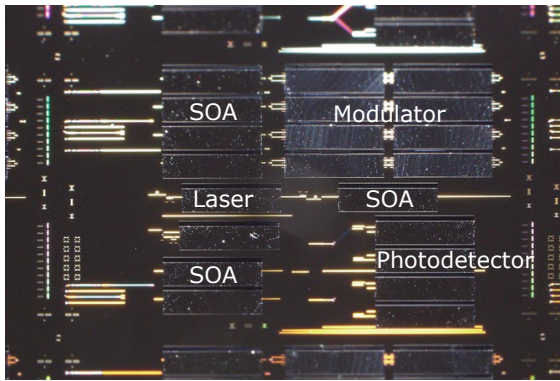


Fig. 3. Photomicrograph after bonding of various types of InP chips on Si photonic circuits that functionally modeled coherent transceivers

III-V compound semiconductor active devices on a Si photonics platform.

3. InP/Si Heterogeneously Integrated Photonic Devices

3-1 Wavelength-tunable lasers

A wavelength-tunable laser fabricated by InP/Si heterogeneous integration is capable of achieving narrow spectral linewidth characteristics in a wide wavelength tuning range by using the InP-based quantum-well structure as the gain region and setting up a wavelength filter consisting of a compact and high Q-factor Si photonic device as a wavelength-tunable mechanism. So far, the obtainment of these characteristics was very difficult for InP-based single-material devices.⁽¹¹⁾ Figure 4 shows the schematic structure of the wavelength-tunable laser that we fabricated.⁽¹²⁾ The cavity layout is configured by an InP-based gain region and Si photonic circuits with ring resonators*⁴ and loop mirrors.*⁵ Wavelength-tuning operation utilizes the Vernier effect*⁶ rendered by combining two ring resonators with slightly different free spectral ranges. Controlling the refractive index through the thermo-optic effect of a micro-heater formed on each ring resonator enables wide wavelength tuning range operation. Furthermore, by leveraging the advantage of the CoW bonding technique enabling the high density integration of various types of InP-based active regions, it is capable of the bonding of InP chips designed for different wavelength bands. Consequently, it allows the expansion of the operating wavelength band for the tunable laser. By utilizing the CoW bonding technique, we integrated wavelength-tunable lasers with different gain regions for the C-band (1,530–1,565 nm) and the L-band (1,565–1,625 nm) on a single Si photonic circuit chip. Moreover, by using a wavelength multiplexer comprising a 2×2 multi-mode interference (MMI) coupler, the optical output of two tunable lasers is emitted from one output port. The optical coupling section between the InP-based gain region and Si waveguide had a two-step tapered waveguide structure consisting of a p-type taper and n-type taper, as depicted in the scanning electron microscope (SEM) image in Fig. 4.⁽⁹⁾ The p-type taper had a two-storied ridge structure

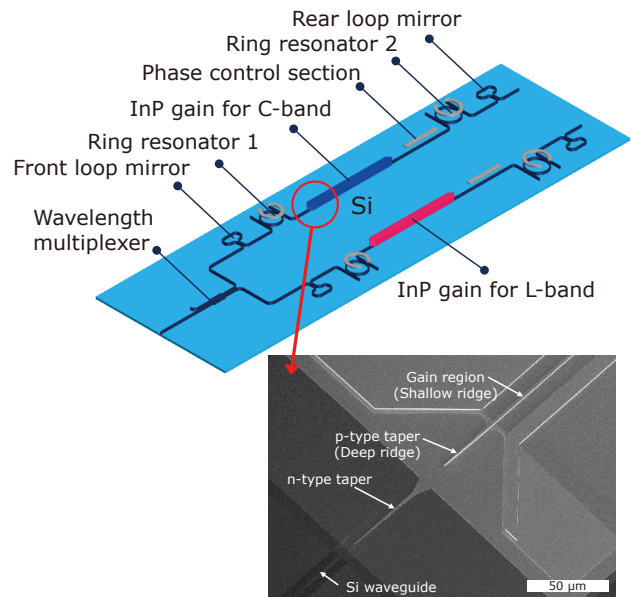


Fig. 4. Schematic structure of single-chip heterogeneously integrated tunable laser for C- and L-bands and SEM image of InP/Si optical coupling section

consisting of a shallow ridge and deep ridge. This structure, which reduces optical coupling loss and its wavelength dependence, is very suitable in the application to wavelength-tunable lasers.

The fabrication procedure of wavelength-tunable lasers using CoW bonding technique is as follows. First, Si photonic circuits for wavelength tuning operation of ring resonators and the like are formed on an SOI wafer by electron beam (EB) lithography. Next, InP chips with GaInAsP multiple-quantum wells (MQWs) are bonded onto Si waveguides using the above-described technique. This is followed by removal of the InP substrate and etching stop layer by wet-chemical etching. As a result, only the laser structure containing the GaInAsP active layer remains on the Si waveguide. The next step is to form a ridge structure in the gain region and a two-step tapered waveguide structure by photolithography and dry etching. Following these process steps, silicon dioxide (SiO_2) cladding layers for Si waveguides, electrodes, and micro-heaters are formed.

The characteristics of this device were evaluated. The evaluation results revealed that the device operates in a wide wavelength tuning range of 104.4 nm, whereby covering the C-band and L-band, as shown in Fig. 5, and achieving extremely wide, quasi-continuous wavelength tuning range operation over 100 nm with 100 GHz channel spacing.⁽¹²⁾ Furthermore, the device exhibits almost constant optical output characteristics and performs single-mode operation with side-mode suppression ratio (SMSR) > 45 dB throughout the wavelength tuning range. These results prove that it is possible to expand the operating wavelength band while maintaining uniform characteristics by bonding two types of InP chips with differently designed active layers. Additionally, the spectral linewidth was estimated based on a frequency noise characteristics. The evaluation results showed that a spectral linewidth of narrower than 50 kHz is obtained for the entire wavelength

tuning range.⁽¹²⁾ Thus, characteristics required as a light source of next-generation digital coherent transmission systems towards multi-Tb/s operation and long-distance transmission were successfully achieved.

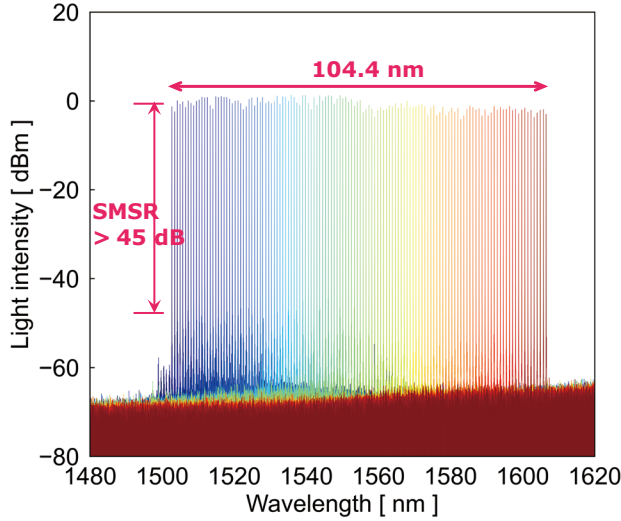


Fig. 5. Superimposed lasing spectra under quasi-continuous wavelength tuning operation of fabricated single-chip tunable laser for C- and L-bands

3-2 MZ modulator

To achieve efficient refractive index (phase) modulation with two differentially driven arms, InP chips with InP-based MQWs, which result in high-modulation efficiency and high-speed operation thanks to nonlinear effects provided by the quantum-confined Stark effect (QCSE),^{*7} are bonded on an SOI wafer in the MZ modulator using InP/Si heterogeneous integration. Furthermore, even as the goal of developing an array for coherent transmission, it is possible to realize a small-footprint array of MZ modulators by utilizing an advantageously small and low-optical-loss Si photonics platform for routing of optical waveguides and a 1×2 MMI branch structure and other features. Figure 6 illustrates the structure of a heterogeneously integrated p-i-n type MZ modulator.⁽¹³⁾ The InP/Si optical coupling section incorporates a two-step tapered waveguide structure.⁽⁹⁾ Regarding high-frequency design, a capacitively-loaded traveling-wave-electrode structure is employed. This structure features a periodic placement of electrodes for adjusting the characteristic impedance and matching the electrical and optical velocity, which is advantageous in terms of reducing capacitance. Moreover, terminating resistors are integrated for impedance matching and decrease of reflections in frequency response.

Figure 7 (a) shows the differential modulation characteristics of the InP-based modulator section. To obtain efficient use of the QCSE, the voltage applied to the upper and lower arms was varied in a differential mode, with a reverse bias of 8 V applied to the modulator section. The high-efficiency modulation characteristics are demonstrated by the product of an effective electrode length (L) of 1.2 mm (total electrode length: 2.0 mm) which considers the filling factor (FF) of the capacitively-loaded travel-

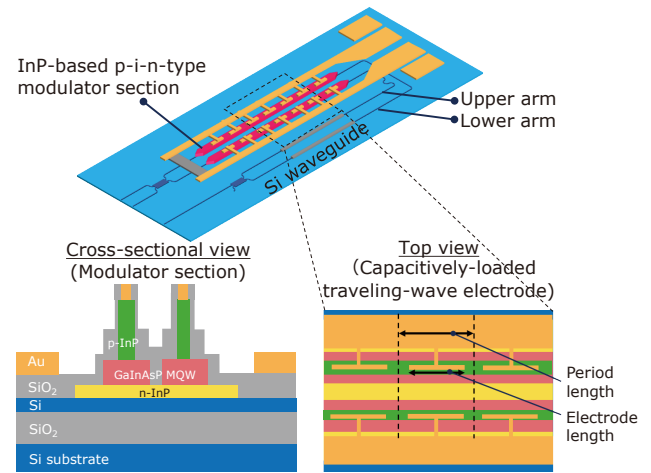


Fig. 6. Structural diagram of heterogeneously integrated p-i-n type MZ modulators

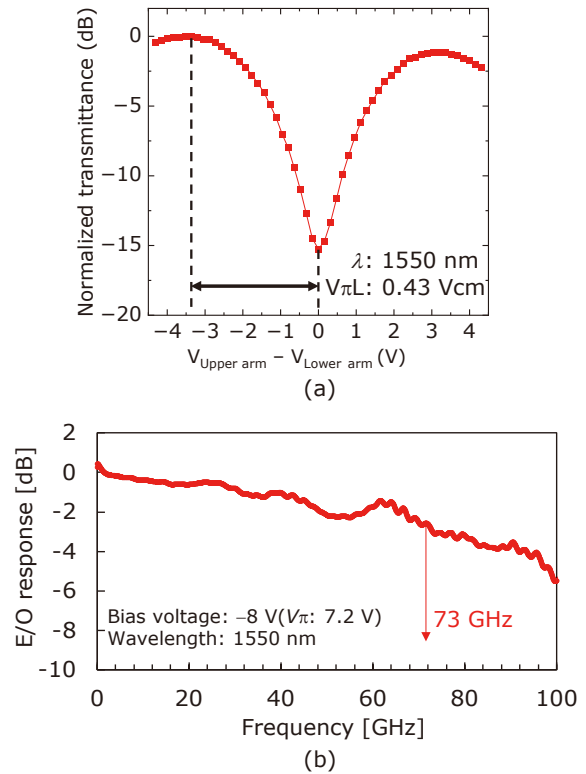


Fig. 7. (a) Extinction characteristics under differential driving of InP-based modulator section (total electrode length: 2 mm, FF: 60%) and (b) frequency response characteristics for EO differential signals (total electrode length: 1 mm, FF: 60%, reverse bias voltage: 8 V) in heterogeneously integrated p-i-n type MZ modulators

ing-wave-electrode structure in the modulator section, and the half-wavelength voltage ($V\pi$); the resulting $V\pi L$ is as low as 0.43 Vcm.⁽¹³⁾ Figure 7 (b) shows the optical frequency response characteristics for high-frequency differential signals (total electrode length: 1.0 mm, FF: 60%, reverse bias voltage: 8 V, $V\pi$: 7.2 V). As normalized at 1.5 GHz, high-bandwidth operation was achieved, with the electrical-to-optical (E/O) 3 dB bandwidth being 73 GHz.⁽¹³⁾

3-3 Photodetector

Figure 8 presents a structural diagram of the InP/Si photodetector we fabricated for coherent transmission.⁽¹⁴⁾ The 90° hybrid⁸ with a 4 × 4 MMI coupler comprising Si waveguides (silicon photonics [SiPH]) was formed by EB lithography. The four-channel p-i-n photodiode (PD) array for in-phase (I-CH) and quadrature (Q-CH) connected to the 90° hybrid, has a deep-ridge structure including a GaInAs absorption layer formed on the Si waveguide. Hence, this structure is configured through the bonding of GaInAs/InP chips on an SOI wafer. The InP/Si optical coupling section uses a two-step tapered waveguide structure, as with other heterogeneously integrated photonic devices.⁽⁹⁾ This device has a size of 1.0 mm × 1.2 mm, being miniaturized to only 20% of that of previously

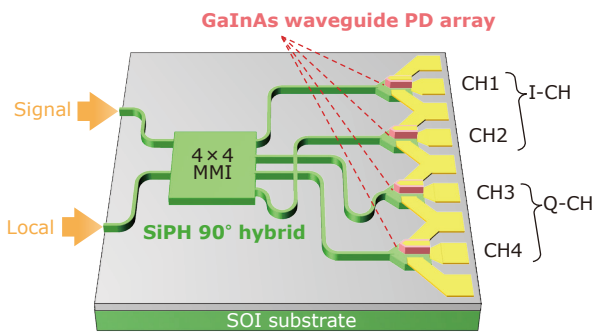


Fig. 8. InP-based p-i-n PD array integrated with 90° hybrids consisting of Si waveguides

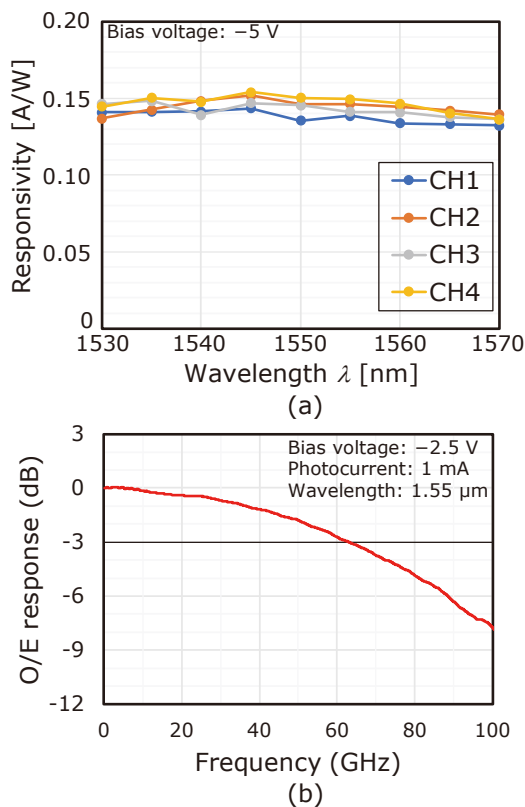


Fig. 9. (a) Wavelength dependence of responsivity and (b) O/E frequency response for InP-based p-i-n PD array integrated with 90° hybrids consisting of Si waveguides

reported InP-based photodetectors⁽¹⁾ thanks to the use of Si photonics.

Figure 9 (a) shows the wavelength dependence of the responsivity for the heterogeneously integrated photodetector.⁽¹⁴⁾ Although optical coupling loss to optical fibers and hybrid splitting optical loss (6 dB) occur in the 90° hybrid, this photodetector demonstrated high responsivity values of more than 0.13 A/W over the C-band, achieved by leveraging the advantages of InP-based PDs. The responsivity imbalance between channels for I-CH and Q-CH was smaller than ± 0.5 dB over the C-band. Figure 9 (b) shows optical-to-electrical (O/E) frequency response of the heterogeneously integrated photodetector.⁽¹⁴⁾ It demonstrated high-bandwidth operation, with the O/E 3 dB bandwidth being 64 GHz at a photocurrent of 1 mA.

4. Conclusion

This paper described the wavelength-tunable laser fabricated by heterogeneous integration using InP chip-on-SOI wafer bonding. This tunable laser exhibited an extremely wide wavelength tuning range operation exceeding 100 nm thanks to the integration of two differently designed gain regions and narrow spectral linewidth characteristics (< 50 kHz) leveraging high Q-factor Si-ring resonators. Additionally, this paper demonstrated high-efficiency, high-bandwidth operation compatible with 100 GBaud, and compactness for MZ modulators and photodetectors by taking advantage of the features of the InP-based active region and Si photonics with InP chip-on-SOI wafer bonding.

This report proved the superiority of InP/Si heterogeneous integration, applying it to photonic devices for 1.5 μ m wavelength digital coherent transmission systems. This technology is capable of the monolithic integration of photonic devices operating in various wavelength bands including the 1.3 μ m wavelength on Si photonics platforms. Therefore, we plan to roll it out widely as next-generation platform technology for photonic devices.

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• ChatGPT is a trademark or registered trademark of OpenAI, Inc. or its subsidiaries in the United States and other countries.

Technical Terms

- *1 III-V compound semiconductor: A semiconductor obtained by combining group III elements with group V elements. III-V compound semiconductors are the direct-transition type and therefore can emit light with high efficiency. Their applications include laser light sources.
- *2 Si photonics: A technology that enables integration of various photonic devices on a Si substrate using microfabrication techniques. A Si optical waveguide exhibits a strong optical confinement effect due to its high refractive index contrast and is excellent in terms of miniaturization and high-density integration in photonic integrated circuits.
- *3 Digital coherent transmission: An optical communication method that superimposes data on both signal light intensity and phase, utilizing the properties of light as electromagnetic waves. Digital coherent transmission provides the advantage of error-free data decoding by using digital signal processing circuits to compensate for the quality degradation of optical signals which is induced at transmitters, receivers, and transmission media (e.g. optical fiber).
- *4 Ring resonator: A device that combines a ring-shaped optical waveguide and a directional coupler or other types of optical couplers. Resonance occurs at the resonant wavelength spacing corresponding to the circumference length of the ring.
- *5 Loop mirror: A reflector formed by a looped optical waveguide structure. The loop mirror works as a reflector by using the loop to return the light divided by a directional coupler or other types of optical couplers.
- *6 Vernier effect: An effect originating from the Vernier calipers, characterized by enhanced intensity due to optical interference at wavelengths where two resonant spectra with different peak spacings coincide.
- *7 Quantum-confined Stark effect: A phenomenon of an exciton absorption peak shifting towards the low-energy side (long-wavelength side) when a quantum-well structure is subjected to the application of a vertical electric field, in which the wave functions of confined electrons and holes into the quantum-well structure undergo spatial separation.
- *8 90° hybrid: An optical waveguide that demodulates transmitted phase signals, utilizing optical interference between the signal and local oscillation.

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