Silicon Photonics Optical Transmitter Technology for Tb/s-class I/O Co-packaged with CPU

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In the near future, Tb/s-class large-capacity input/output (I/O) circuits are considered to be necessary for high-end CPUs used in high-performance computing (HPC) systems and high-performance servers due to the progress in processing performance of the CPUs. A high-performance I/O using optical transmission technology is attracting public attention as a technology to overcome the limitations of a conventional electric I/O in terms of size and power consumption. Particularly, an integrated optical I/O chip based on silicon (Si) photonics technology is a very promising candidate to realize a Tb/s-class large-capacity I/O chip of a size that allows it to be co-packaged with a CPU. This paper describes the current status of progress in Fujitsu Laboratories' approaches to develop the Si optical transmitter for a large-capacity optical I/O chip. To realize the co-packaging of a large-capacity optical I/O chip in a CPU package, it is essential to realize a Si optical transmitter that ensures stable operation with low power even under drastic fluctuations of operation temperature. Therefore, the authors proposed a novel Si optical transmitter scheme using a highly energy-efficient Si ring modulator to operate stably without a complex wavelength-tuning procedure. A prototype integrated optical transmitter based on this scheme was fabricated and evaluated. The evaluation results showed that an integrated Si optical transmitter chip could operate at 10 Gb/s without any wavelength tuning over a temperature range of 25 to 60°C. Further, supported by successful developments of a compact-size, high-performance laser source using flip-chip bonding technology as well as a 4-ch integrated Si hybrid laser array for wavelength division multiplexing, there are certain prospects for application of a Si optical transmitter for large-capacity optical I/O chips.

1. Introduction

With regard to high-end CPUs boarded on the high-performance computing (HPC) systems and high-performance servers, the total bandwidth necessary for inputting and outputting data between inside and outside of the package in which the CPU is mounted has increased year by year, accompanying the increase in the number of integrated cores. In the near future, Tb/s-class interconnection among CPUs will become necessary. High-speed input/output (I/O) technology using optical transmission is characterized by several advantages including the fact that it is unlikely to cause waveform degradation or crosstalk during transmission. Therefore, it is considered as a promising technology to realize an interconnection among CPUs with reduced size and higher performance by overcoming the limitations of conventional electric I/O technology.

Among others, silicon (Si) photonics has been attracting public attention recently as a technology that makes extremely compact, high-density, optical integrated circuits feasible.[1)] In the case of Si photonics, an optical circuit is processed on a large-diameter silicon-on-insulator (SOI) substrate with existing semiconductor process technology by using a low-loss, compact-type Si optical waveguide as a basis. Accordingly, this technology allows a higher level of integration compared to the conventional compound semiconductors or optical circuits on a glass substrate. Besides, it has the possibility of producing highly functional optical devices at low cost and high yield. Further, if the transmission capacity per single transmission line (optical fiber) can be increased to a level higher than 100 Gb/s by using wavelength division multiplexing (WDM) technology which multiplexes multiple optical carrier signals onto an optical fiber by using different wavelengths of laser light, then Tb/s-class optical interconnection among CPUs may be achieved with fewer transmission lines. Based on these advantages, Fujitsu Laboratories is promoting the development of device technologies with the purpose of realizing a Tb/s-class, large-capacity, optical interconnection employing a Si photonics integrated optical I/O chip copackaged in the same CPU package as illustrated in **Figure 1**.

This paper introduces the current approaches of Fujitsu Laboratories to develop a Si optical transmitter, which is a transmitter for large-capacity optical interconnection. First of all, this paper describes our proposed concept and configuration of an optical transmitter without the need for a wavelength-tuning procedure and demonstrates the operation at 10 Gb/s without the need for a wavelength-tuning procedure over a temperature range of 25 to 60°C using a prototype chip of an integrated transmitter. Then, it explains the characteristics of a Si hybrid laser using precise flip-chip bonding technology for a compact, high-performance laser source that is applied to an optical transmitter without the need for a wavelength-tuning procedure. Finally, it introduces development for wavelength division multiplexing of this optical transmitter, showing the development result of a 4-ch Si hybrid laser array where a Si hybrid laser with different wavelengths is integrated on a single chip.

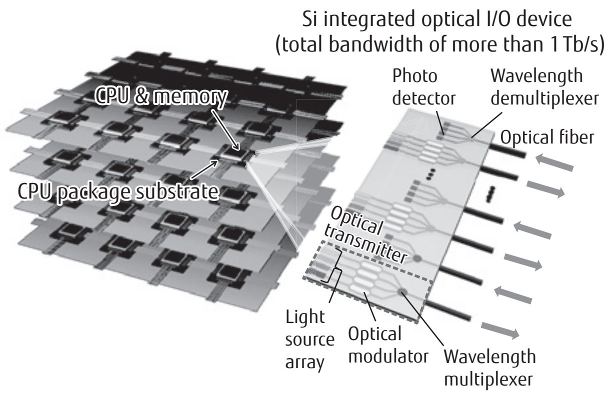


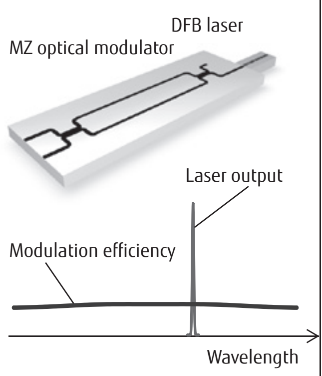
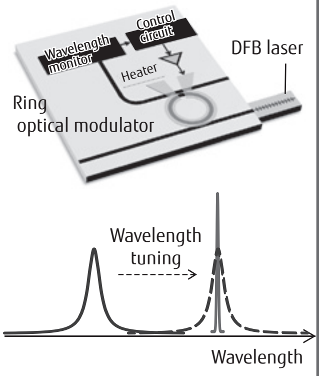
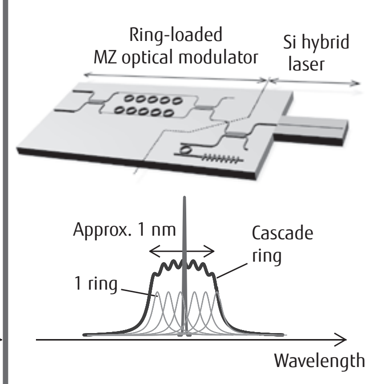
Figure 1
Large-capacity optical interconnection among CPUs using Si integrated optical I/O device.

2. Operation of high-efficiency Si optical transmitter without the need for wavelength tuning

In general, low-power-consumption operation is required for high-speed I/O circuits for interconnection among CPUs due to limitations on power supply to the CPU package and cooling. On the other hand, when a Si integrated optical I/O device is implemented within a CPU package as illustrated in Figure 1, it is difficult to stabilize the temperature of the Si integrated optical I/O device by using a Peltier device due to difficulties on space and power consumption. Therefore, the operation temperature is likely to fluctuate corresponding to the change in CPU load. Accordingly, we investigated the configuration of the optical transmitter in order to solve these challenges, because the integrated I/O device that we are going to develop needs to realize stable, low-power operation under a fluctuating temperature environment.

The optical transmitter to be used in the Si integrated optical I/O device is comprised of a single-wavelength continuous wave (CW) laser source, optical modulator that modulates the signal light with an electric signal data array, and optical multiplexer that multiplexes the signal light of multiple wavelengths into a single transmission line. In this context, the power consumption of the optical transmitter is determined mainly by electricity—light conversion efficiency at the laser light source and modulation power at the optical modulator. Because Si as an indirect transition-type semiconductor does not have a high-efficiency light-emitting function in the laser source, an approach to combine this with an optical device based on a direct transition-type semiconductor such as InP is promising. Meanwhile, with regard to the optical modulator to be used for Si photonics, mainly two methods, i.e., a Mach-Zehnder (MZ) optical modulator and ring modulator, have been reported so far. As illustrated in **Figure 2**, an MZ optical modulator has a very wide operating wavelength range, which makes wavelength tuning unnecessary. However, because of its low modulation efficiency, its power consumption tends to be high.

With regard to the ring modulator, on the other hand, the signal light is confined within a ring resonator as small as only several μm and optical modulation is conducted by using a resonance effect; therefore,

Configuration	Conventional configuration 1 (MZ optical modulator)	Conventional configuration 2 (ring optical modulator)	Proposed configuration (optical transmitter without wavelength tuning procedure)
Device structure and wavelength arrangement			
Modulation efficiency	Low	High	Relatively high
Operation wavelength range	Very wide	Narrow (0.1 nm)	Wide (approx. 1 nm)
Temperature tolerance	Very wide	Narrow	Wide (20 to 30°C)
Wavelength tuning	Not necessary	Necessary	Not necessary

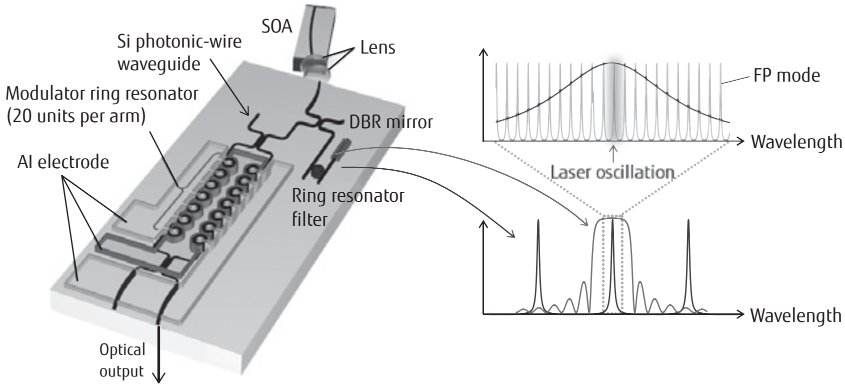
DFB: Distributed Feedback

Figure 2
Optical transmitter methods used in Si integrated optical I/O device.

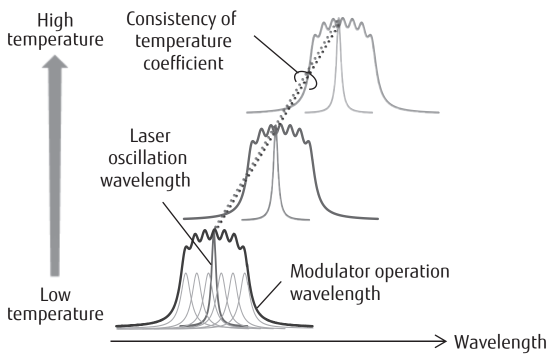
the modulation efficiency is high. This makes it advantageous in terms of reducing power consumption. However, the operation wavelength range of the ring modulator is limited to only 0.1 nm around the peak of ring resonance. In addition, this operation wavelength shifts when there is a temperature change. Therefore, to ensure stable operation of the ring modulator, a wavelength-tuning system should be boarded on the modulator to provide continuous tuning so that the operation wavelength of the modulator can match the source wavelength. However, in such a case, the entire size and power consumption of the optical transmitter must be increased because space is required for the wavelength-tuning system and power is needed to drive the system.

To eliminate the above-mentioned trade-off between modulation efficiency and wavelength tuning in the conventional optical modulators and to realize a high-efficiency optical transmitter without the need for wavelength tuning, we proposed an optical transmitter that does not require wavelength tuning (see the right column in Figure 2). In this optical transmitter, a Si hybrid laser as a laser source and a ring-loaded MZ optical modulator as an optical modulator are combined. The ring-loaded MZ optical modulator has a structure based on a cascade connection of multiple ring resonators of the same type in both arms of an MZ interferometer. In each ring resonator, PIN-type phase shifters are formed along the circumference and optical modulation is conducted by applying the voltage to these shifters. While the individual ring resonator used in this modulator is designed to show a somewhat lower resonance efficiency than the aforementioned ring modulator, and it shows a somewhat low modulation peak efficiency and wider operation wavelength, it achieved a high modulation efficiency and a wider operation wavelength range (approx. up to 1.0 nm) as a whole modulator. This was achieved by adopting a cascade connection of the ring resonators while giving consideration to the manufacturing-related variability of the peak wavelength.[2] A Si hybrid laser is an external resonator type of laser source comprised of an InP-based semiconductor optical amplifier (SOA) and a Si wavelength selection mirror on a Si chip. By using light emitting/amplifying functions over a wide wavelength range of approx. 100 nm offered by the SOA, laser oscillation is achieved in the single wavelength determined by a Si wavelength-selection mirror. A Si wavelength-selection mirror is comprised of a ring resonator filter and a distributed Bragg reflector (DBR) mirror, where only the light corresponding to a single peak of the ring resonator selected within the refection wavelength bandwidth of DBR mirror is reflected. It results in a laser oscillation at the single wavelength although there are multiple ring resonator peaks existing in a periodic manner [**Figure 3 (a)**]. Based on the above mechanism, the oscillation wavelength at this laser is always locked to the peak wavelength of the ring resonator. Further, in the proposed optical transmitter, a consistent wavelength between the light source and the optical modulator can be achieved by adopting a ring resonator filter of the same structure for both the optical modulator ring resonator and the Si hybrid laser ring resonator. Further, because both ring resonators have an identical temperature coefficient,[3)] no special wavelength tuning is necessary, even if there is any fluctuation in the operation temperature of the optical transmitter. In such a case, the wavelength of laser oscillation and the operation wavelength of the modulator will be synchronized and shifted [**Figure 3 (b)**].

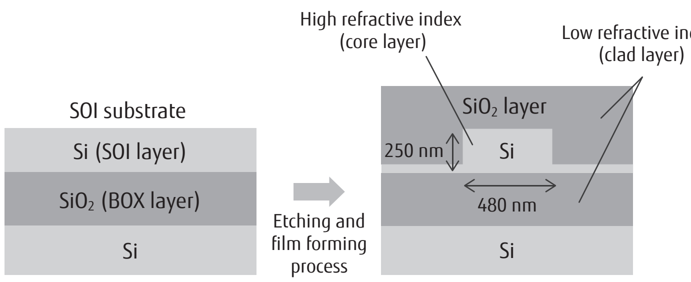
To demonstrate the concept of the above-mentioned operation without the need for wavelength tuning, a prototype integrated optical transmitter chip was fabricated and its characteristics in 10 Gb/s modulation operation were evaluated. The optical wire configuration inside the optical transmitter chip is comprised of a rib-type Si optical waveguide with a width of 480 nm and height of 250 nm. After etching an upper Si layer of Si-on-insulator (SOI) substrate, a SiO_2 clad layer is formed on the upper side [**Figure 3 (c)**]. The



(a) Structure of integrated optical transmitter and laser wavelength selection mechanism



(b) Wavelength shift at temperature change



(c) Cross-sectional structure and manufacturing method of Si photonic-wire waveguide

Figure 3
Optical transmitter without wavelength tuning procedure.

entire length of the integrated optical transmitter chip is approx. 2 mm. The ring resonators arranged in the laser source and those arranged in the optical modulator are identical types of ring resonator with a curvature radius of 7.2 μm and peripheral length of approx. 50 μm. These ring resonators are arranged on each arm of an optical modulator at 30 μm intervals (i.e., a serial arrangement of 20 resonators in total). With regard to the ring resonator of the modulator, p+-Si and n+-Si doping areas are formed on the right and left of the i-Si waveguide core respectively, and both channels are connected to an Al electrode. By injecting a free carrier in the waveguide core layer via the Al electrode, the refractive index of waveguide will change, and this results in changing the signal light phase. In the current experiment, pseudo-random binary sequence (PRBS) of 10 Gb/s with an amplitude of 3.7 Vpp (2^7–1 pattern) was input into the modulator electrode after a bandwidth correction. Further, in the operation experiment of this chip, oscillation of the Si hybrid laser was realized by building an optical coupling between Si transmitter chip and InP-SOA chip via a lens. The relationship between the laser oscillation wavelength and the modulator operation wavelength in the temperature range of 25 to 60°C is indicated in **Figure 4**. With the increase in chip operation temperature, it was observed/confirmed that the laser oscillation wavelength and the modulator operation wavelength shifted to the long wavelength side in synchronization. As a consequence, a favorable eye pattern with a dynamic extinction ratio higher than 6 dB was confirmed when examining the modulation signal eye patterns obtained at each temperature. Based on these experiment results, it was confirmed that the high-efficiency Si optical transmitter proposed in the current project could be operated at 10 Gb/s without the need for wavelength tuning.[4)]

3. Size reduction and performance enhancement of Si hybrid laser

Based on the above-described experiment results from the 10-Gb/s operation of a high-efficiency Si optical transmitter without wavelength tuning, we saw a prospect to use a high-efficiency ring modulator without a complicated wavelength-tuning procedure. However, the configuration based on the lens coupling of an SOA chip and Si chip was bulky. To mount this device within a CPU package, further size reduction was necessary. In addition, to realize a faster transmission in an optical I/O device, higher output performance of the laser is required. Accordingly, we began working to reduce the size of the Si hybrid laser and enhance its performance by using high-precision flip-chip bonding technology.

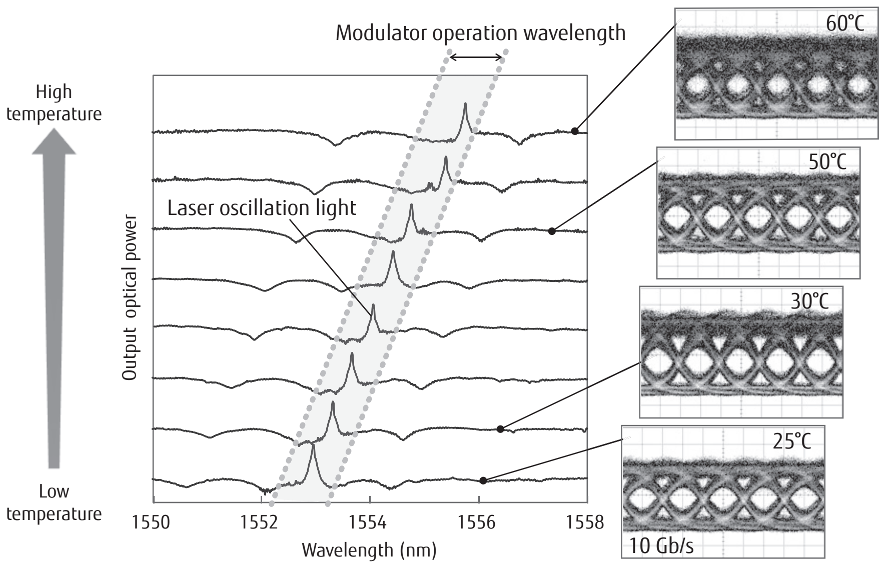
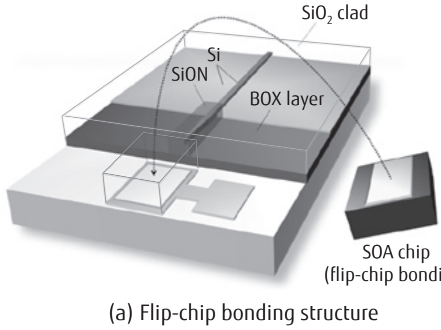
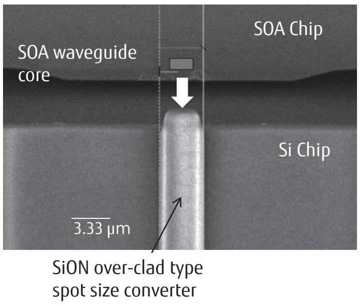


Figure 4
10 Gb/s operation characteristics of integrated optical transmitter at 25–60°C.

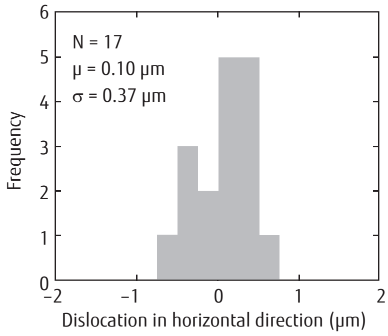
In the lens-coupling-type Si hybrid laser, there was a limitation in the performance due to a large optical coupling loss between the SOA and Si chips. Therefore, as indicated in **Figure 5 (a)**, an SOA chip was directly bonded on the Si chip by flip chip bonding and we expect this will lead to a drastic improvement of the characteristics by having highly efficient optical coupling of both chips. Besides, because there is no element other than the SOA chip and Si chip in this configuration, the entire size of the laser unit can be reduced drastically. To achieve a high optical coupling efficiency in such a hybrid implementation mode, it is imperative to ensure spot size matching between both waveguides and the positioning matching between both waveguides. Nevertheless, there was an issue of spot size mismatching, because optical signals were stringently confined in an extremely small waveguide core with regard to the Si optical waveguide, which made the spot size in the waveguide edge smaller (approx. 1 μm) than the spot size of the SOA waveguide edge (2 to 3 μm). Accordingly, Spot Size Converter (SSC) technology was developed. In this technology, a 3 × 3 μm dielectric (SiON) waveguide core was formed to cover the optical I/O section on a Si optical waveguide with the purpose of migrating the optical power transmitted through the Si optical waveguide into a waveguide mode suitable for a dielectric waveguide with a larger spot size [**Figure 5 (b)**]. By adopting this technology, the spot size of both waveguides at the Si-SOA coupling interface has become almost the same (approx. 3.0 μmϕ), allowing a higher optical coupling efficiency. Following this approach, we developed a high-precision flip chip bonding technology to realize a positioning matching between both waveguides. By using a technology to recognize a precise marker image and optimizing the device structure, a highly precise and highly uniform mounting was realized as shown in **Figure 5 (c)** with an average dislocation of both waveguides of 0.10 μm in the horizontal direction and with a dispersion level of 0.37 μm. The characteristics of the prototype flip-chip bonding Si hybrid laser fabricated by using the aforementioned technologies are indicated in **Figure 6**. The entire laser length was drastically reduced from several cm to 1.6 mm. The oscillation threshold current for the laser has been decreased from 48 to 9.8 mA, and an optical output of 15.0 mW has been achieved when the



(a) Flip-chip bonding structure



(b) SEM image of Si-SOA interface section



(c) Bonding location accuracy at flip-chip bonding

Figure 5
Si hybrid laser using flip-chip bonding.

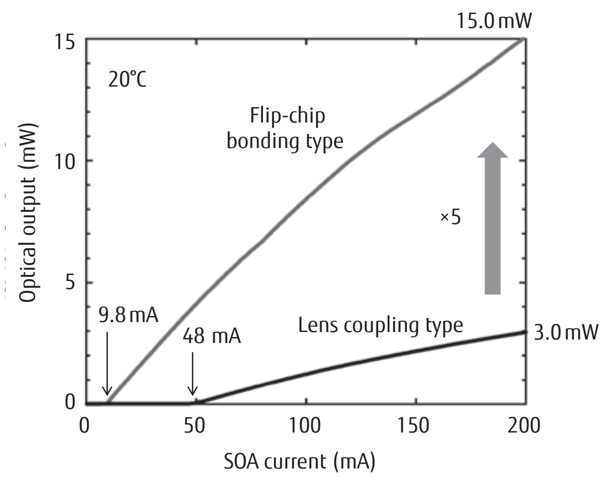


Figure 6
Characteristics of flip-chip bonding Si hybrid laser.

device was driven at 200 mA. This output is approx. five times the conventional level. Based on analysis of the oscillation threshold level, it was confirmed that the optical coupling loss between Si and SOA was decreased from 4.0 to 1.6 dB. Further, with regard to the electric–optical conversion efficiency of this laser evaluated at 20 to 60°C, the optimal level was achieved with 4.5 to 7.6% among Si hybrid lasers of a similar type.[5)]

4. Development for the wavelength multiplexed transmitter

Based on the development achievements described in the previous sections, we saw a prospect of realizing low-power operation of a single-channel optical transmitter to be used in an integrated I/O device across a wide operation temperature range. This section describes an approach to realize wavelength multiplexing transmission, which is one of the great advantages of the integrated I/O device using Si photonics technology.

To achieve stable wavelength multiplexing transmission under a fluctuating temperature environment, a suitable wavelength multiplexing method should be selected so that favorable wavelength channel multiplexing/demultiplexing can be achieved by an optical multiplexer/demultiplexer arranged in the transmission/receiving section. A specific wavelength multiplexing method that is considered to be promising is the Coarse WDM (CWDM) method, as it can compensate for the operation wavelength difference and the temperature-induced wavelength fluctuation in each optical component by means of relatively wide wavelength channel spacing without conducting active wavelength tuning in each channel. In this case, a multi-channel optical transmitter without the need for wavelength tuning is necessary that operates at wide and uniform wavelength spacings larger than 10 nm in the optical transmission unit. Therefore, we fabricated a prototype 4-ch Si hybrid laser array to be used in the multichannel optical transmitter of the CWDM method and validated its operation characteristics. A schematic drawing of the upper face of the 4-ch Si hybrid laser array device is shown in **Figure 7**. This device has a configuration where a 4-ch SOA array is mounted by block flip-chip bonding on a Si chip on which a 4-ch Si wavelength selection mirror is integrated. The device size is approx. 1.8 × 1.1 mm. The aforementioned two technologies are used for optical coupling of a Si optical waveguide and SOA waveguide. Even in the block flip-chip bonding of a 4-ch SOA array, waveguide dislocation at all channels is less than 0.5 µm, indicating a favorable result. In the 4-ch Si wavelength selection mirror, the same ring resonator filter is used on all channels so that a common CWDM wavelength grid can be formed based on these filtering characteristics. Meanwhile, the DBR mirror in each channel was designed so that each channel should select four different ring resonance peaks by shifting the center wavelength of reflection with a tuning of the grating period. By using the above-mentioned wavelength-selection mirror configuration, it is possible to arrange the laser oscillation wavelength of each channel at uniform wavelength spacings determined by the peak interval of the ring resonators (FSR: Free Spectral Range) without highly precise dimension adjustment. Further, in the case of integration with a ring-loaded MZ optical modulator, it is possible to adjust the laser oscillation wavelength of each channel automatically to the modulator operation wavelength by making sure that the ring resonator filter of each optical modulator is designed in the same manner as the ring resonator filter of the laser array. The oscillation spectra of all four channels are shown in **Figure 8** when they are simultaneously driven by an SOA current of 70 mA. The laser threshold current for each channel is as low as 12 to 19 mA, where low-loss Si-SOA optical coupling is realized even with 4-ch block bonding. In the oscillation spectrum, stable laser

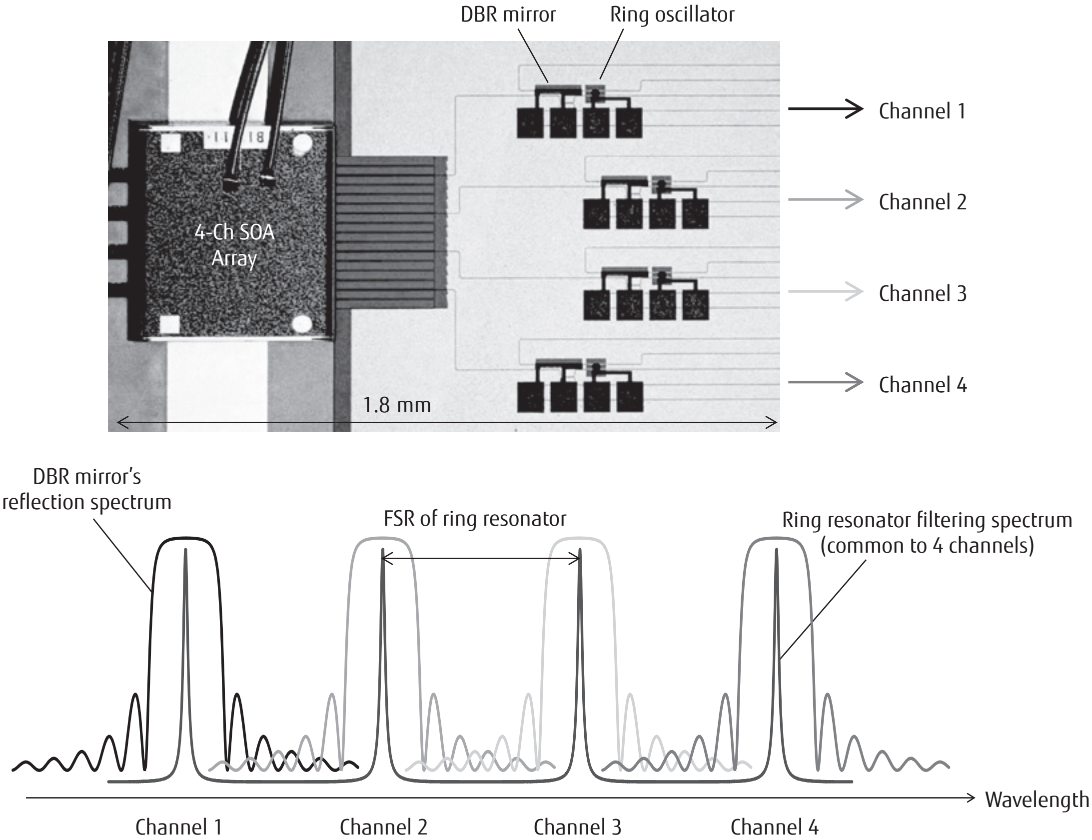


Figure 7
Structure of 4-ch Si hybrid laser array.

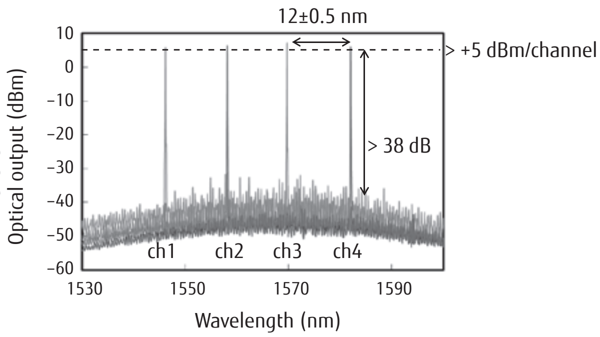


Figure 8
Oscillation spectrum of 4-ch Si hybrid laser array.

oscillation at four channels was confirmed at a wavelength spacing of 12±0.5 nm, which corresponds to the ring resonator FSR. Besides, a sufficiently high optical output higher than +5 dBm was observed and a high Side Mode Suppression Ratio (SMSR) higher than 38 dB was obtained in each channel. Thus, the high basic performance applicable to a CWDM method 4 wavelength channel optical transmitter was confirmed.[6)]

5. Conclusion

This paper described the current development status of a Si photonics optical transmitter to be applied to a Tb/s-class large-capacity optical interconnection for HPC systems and high-performance servers. To realize low-power operation of a Si optical transmitter under the influence of temperature fluctuations, a concept of an optical transmitter without the need for wavelength tuning was proposed by combining a Si hybrid laser and ring-loaded MZ optical modulator. Further, based on an evaluation of a prototype chip, the feasibility of 10 Gb/s operation without the need for wavelength tuning at 25 to 60°C was demonstrated. In addition, fabrication of prototype devices and validation of their operations were carried out also to evaluate the size reduction and performance enhancement based on flip-chip bonding technology on a Si hybrid laser as well as the high uniformity and high-performance operation of a 4-ch Si hybrid laser array for CWDM-method wavelength multiplexing transmission.

In future, we plan to complete the Si integrated optical I/O device by promoting the development of optical receivers and optical multiplexers/demultiplexers to be combined with the current optical transmitter. At the same time, we will promote the development of packaging technology to board the Si integrated optical I/O device within the CPU package so that Tb/s-class large-capacity optical interconnection can be realized.

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