Uncooled Operation of Si Mach-Zehnder Modulator Integrated with Membrane Semiconductor Optical Amplifiers inside Interferometer Arms

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Abstract: Membrane SOAs are integrated inside the interferometer arms of Si-MZM, in which the SOAs have on-chip gain of 11-5.3 dB at 25-80℃. In this configuration, SOAs can be used in saturated region suppressing pattern effect. © 2023 The Author(s)

1. Introduction

A Si-based Mach-Zehnder modulator (MZM) is a key component of optical transmitters because it provides high throughput using advanced modulation formats and is monolithically integrated with optical components such as a polarization rotator and polarization beam coupler using mature Si photonics technologies. Digital coherent optical transceivers comprising Si-MZMs have been demonstrated with uncooled operation resulting in low-power consumption. There is a growing demand for high-capacity transceivers; therefore Si-MZMs with higher baud rates are desired. However, to increase the modulation speed and the modulation efficiency, the doping concentration of the Si phase shifter must be increased, which results in an increase of optical loss.

A semiconductor optical amplifier (SOA) is an excellent candidate for compensating for the optical loss of MZMs, as well as other passive device losses, to ensure high output power. Recently, the integration of an SOA in an output waveguide of an MZM has been reported to boost output power, with which a 10-dB gain was obtained with a 100-mA injection current to the SOA [1]. However, uncooled operations have not been demonstrated in SOA-integrated MZMs although an advantage of Si-MZMs is their capability of uncooled operation that is a promising way to reduce the power consumption. Furthermore, reducing power consumption in SOAs is also important.

We have developed membrane III-V devices, which are suitable for integration with Si photonics devices because the thin-membrane structure is easy to couple with Si waveguide. When we design SOAs with a high optical confinement factor and small active volume [2], the device exhibits a high optical gain with low power consumption even at high temperature. However, in such SOA design, the saturation input power is relatively low, which causes a degradation of the signal quality by the pattern effect where gain depends on optical signal pattern when the SOA operates in the saturation region. To overcome this issue, we have proposed a device in which SOAs are placed behind the phase shifters and inside the interferometer arms of the MZM [3]. In this configuration, the intensity change in the arms is small; therefore, the pattern effect is expected to be small even when the SOA is operated in the saturation region. Moreover, the optical power input into the SOA becomes low compared with the out-arm SOA configuration due to the dividing of the light by a multimode interferometer (MMI); therefore, high optical gain is ensured. In our previous work, we have integrated an MZM using InGaAsP phase shifters with membrane SOAs in the arms on a Si platform, and successfully demonstrated high output power of 6 dBm. However, there are no experimental result showing the advantage of the in-arm configuration in terms of the pattern effect and uncooled operation.

In this work, we integrated the membrane SOAs inside the arms of a Si-MZM fabricated by a Si photonics foundry. Since the optical loss of Si phase shifters is much larger than that of the InGaAsP phase shifters, the membrane SOA with low-power consumption and high gain has more beneficial. The integrated SOAs provide on-chip gain of 11-5.3 dB at 25-80℃ with a large fiber input power of 13 dBm. The injection current of each SOA is 30 mW, and the total power consumption of the two SOAs is 136 mW. We confirmed that the proposed SOA configuration suppresses the pattern effect. Using the fabricated membrane-SOA-integrated Si-MZM, uncooled operation for 20 Gbit/s-NRZ signal is demonstrated.

2. Device structure

Figure 1 shows schematics of cross-sectional view of (a) the Si phase shifter and (b) SOA, and (c) top view of the Si-MZM with membrane SOAs. The Si-MZM consists of MMIs and 4-mm-long depletion-type Si phase shifters.

The 300-μm-long SOAs consist of an InGaAsP-based multiple quantum well (MQW) core (width of 750 nm; thickness of 100 nm) buried in a 230-nm-thick membrane InP layer, and they have a lateral *p-i-n* junction. The optical confinement factor in the quantum wells is calculated to be 9%. Since the active area is small and the optical confinement factor is high, it is expected to obtain a large gain with a small injection current even if at a high temperature. For heterogeneous integration of the SOA, the SiO_2 film on the Si photonics substrate was planarized by chemical mechanical polishing, and the InP substrate containing the MQW layer was directly bonded onto the Si photonics substrate by oxygen-plasma-assisted bonding technique. The MQW layer was removed except for SOA active region, and buried regrowth of InP was performed to form the buried heterostructure. Then, we fabricated the lateral *p-i-n* junction. Figure 1(e) shows an optical micrograph of a fabricated device. The details of fabrication process are described in [4].

The SOAs and Si phase shifters are optically connected by the Si waveguide inside the interferometer arms. Since the effective refractive index of a standalone membrane SOAs are close to that of a Si waveguide, the SOA is easy to optically connect with low coupling loss by using simple tapered InP waveguides, as shown in Fig. 1(d).

In the in-arm SOA configuration, the optical input power to the SOA is relatively low because the light is divided by the MMI and passes through the Si-phase shifter; therefore, high optical gain is ensured. In addition, since there is a phase change but a small intensity change after it has passed through the Si phase shifter, signal degradation due to the pattern effect is expected to be suppressed even when the SOA is operated in the saturation region. For these reasons, we can design the SOA with a large optical confinement factor in quantum wells, which results in an SOA with high optical gain and a low power consumption.

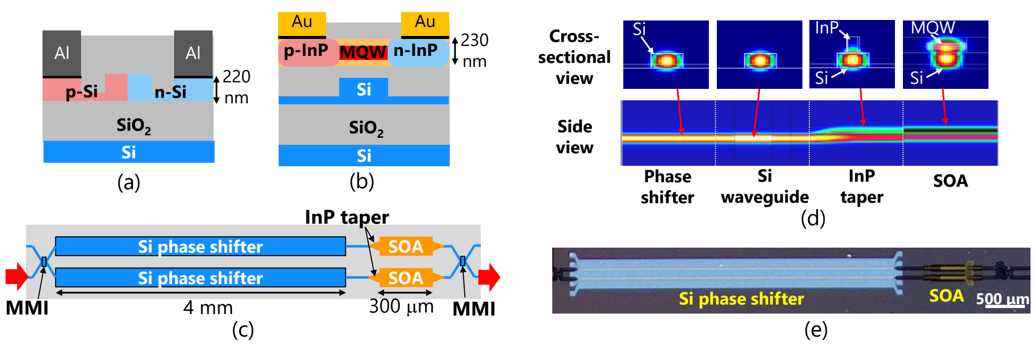

Fig. 1. Schematics cross-sectional views of (a) Si phase shifter and (b) SOA, and (c) top views of device configuration, (d) calculated optical mode transition from Si phase shifter to membrane SOA. (e) Optical micrograph of a fabricated device.

3. Results and discussion

First, we measured the characteristics of the integrated SOAs. The input light from an external tunable laser diode was coupled from a lensed optical fiber to the Si waveguide after polarization control to the transverse electric (TE) mode. The coupling loss between the fiber and the Si waveguide was about 2 dB. Figure 2(a) shows the measured on-chip gain versus wavelength (13-dBm input power) for stage temperatures of 25 and 80℃, where the gain was estimated from the difference in the transmitted power of a reference MZM without SOAs. The injection current into each SOA was 30 mA, and total power consumption of the two SOAs was 136 mW. The on-chip gain of more than 10 dB is obtained despite the small injection current of 30 mA at 25℃. For 80℃, 5.3-dB on-chip gain was obtained at the wavelength of 1560 nm.

Next, we evaluated dynamic response of the SOA-integrated Si-MZM, where the RF signal was input to the MZM using an RF probe with biasing at 2.1 V_{dc}. For comparison, dynamic response of a MZM with out-arm SOA configuration was also measured. Figure 2(b) shows the measured E-O response for in- and out-arm SOA configurations, where the injection current into each SOA was 10 mA and fiber input power was 14 dBm, which is in the saturation region in either configuration. In the out-arm configuration, there is a gain recovery in the low-frequency region which affect signal degradation due to the pattern effect. However, in the in-arm configuration, it was clearly shown that the gain recovery behavior is negligible even in the saturation region. Note that the decrease in E-O response with increasing modulation frequency in the in-arm SOA configuration is due to the modulation bandwidth of the Si-MZM.

Finally, we measured eye patterns for a 20-Gbit/s NRZ signal with the laser wavelength was set to be 1560 nm and the injection current into the each SOA is 30 mA. Figure 3(a) show the measured eye diagrams with input power of 14 dBm at 25°C for different pseudo-random bit sequence (PRBS) of 2^7-1, 2^{15}-1, and 2^{31}-1. The eye diagrams for all PRBS were clearly opened without significant pattern effect, where the input power was in the saturation region in the SOA. Figure 3(b) shows measured on-chip gain versus fiber input power, and the measured eye diagrams at 80°C for different input power. Although the input power of 14 dBm is in the saturation region, there is no observable signal degradation while the signal to noise ratio increases to 4.9 from 4.5 by increasing the input power. These results show that the in-arm SOA configuration enables us to suppress the pattern effect and is suitable for membrane SOAs with a small active area and high optical confinement factor.

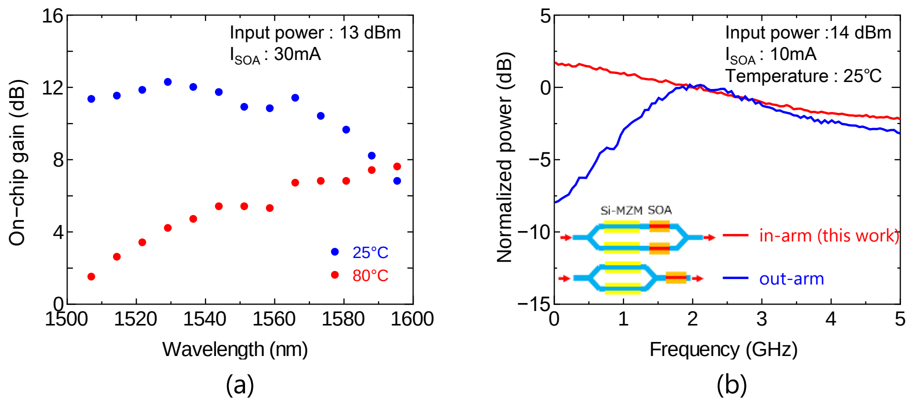

Fig. 2. (a) Measured on-chip gain versus wavelength. (b) Measured E-O responses for in- and out-arm SOA configurations.

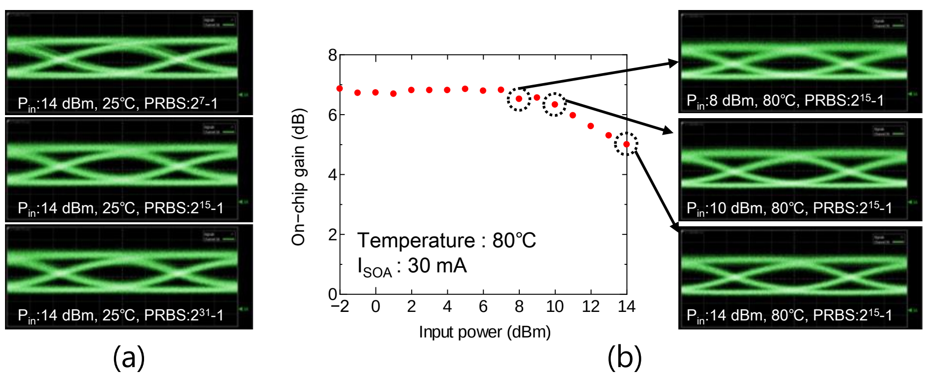

Fig. 3. (a) Measured eye diagrams for different PRBS at 25°C. (b) Measured on-chip gain versus fiber input power at 80°C, and measured eye diagrams for different input power.

4. Conclusion

We have integrated III-V membrane SOAs inside the interferometer arms of a Si-MZM. The SOAs have on-chip gain of 11-5.3 dB at 25-80°C. Measurement of the E-O responses and eye patterns clearly show that the pattern effect is suppressed by placing the SOAs in the interferometer arms of the MZM. The SOA can be used in the saturated input power region, allowing it to operate in an uncooled condition.

5. References

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