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High Speed and Low Power Consumption Silicon Thermo-optical Phase Shifter

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Abstract

We demonstrated the low power consumption and high speed operation of silicon waveguide phase shifter with directly heating structure using multi-mode interference. The power consumption for π-phase shift was 13.1 mW with 7 μs switching time.

1. Introduction

Silicon has about 10 times larger thermo-optic constant than that of silica, so it is possible to control the characteristics of silicon waveguide device with small footprint and low power consumption micro-heater [1]. In particular, π-phase shift power of 12.7 mW and high speed operation of 2.4 μs have been reported in the heater structure which directly energizes silicon [2]. In this letter, we proposed an electrode structure with low insertion loss using multi-mode interference (MMI) and succeeded in demonstrating phase shift operation at high speed and low power consumption.

2. Structure of MMI phase shifter

Although direct heating of silicon can widely control the phase of propagation lightwave with high speed and low power consumption, an increase in insertion loss of the electrode to inject current into waveguide becomes a problem. We proposed a direct heating structure with low insertion loss using characteristics in multi-mode interference. The structure of the designed phase shifter is shown in Fig. 1.

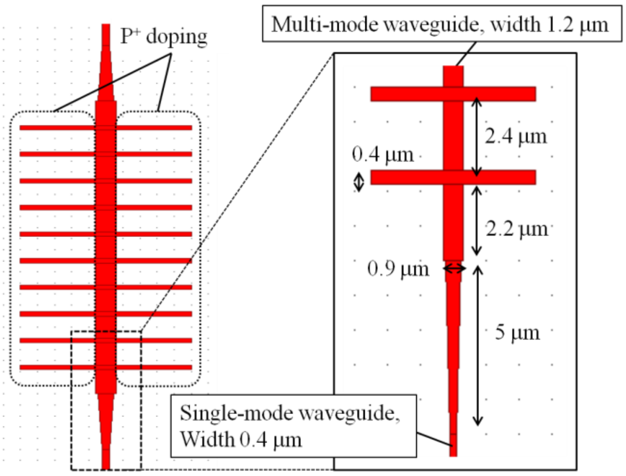

Fig. 1. Design of MMI phase shifter.

The basic principle is a phase shifter that utilizes the thermo-optical effect of silicon. The phase modulation part is the multi-mode waveguide. Single-mode waveguide with a width of 400 nm and a height of 220 nm is connected to multi-mode waveguide with a width of 1.2 μm via a taper. Silicon electrodes with a width of 400 nm are formed 10 periods with 2.4 μm interval at both sides of the multi-mode silicon waveguide core. The light introduced from the single-mode waveguide to the multi-mode waveguide concentrates at the center of the waveguide at a period of 2.4 μm due to the multi-mode interference effect. Therefore, it is hardly affected by the silicon electrode at the sidewall of the multi-mode waveguide. Calculated mode field of MMI phase shifter is shown in Fig. 2(a). Therefore, direct current injection is possible while reducing optical loss [3]. When the silicon waveguide is directly energized and heated, the refractive index changes, so that a phase shift operation can be obtained. This electrode is heavily p-type doped (concentration of 1×10^{19} cm^{-3}). On the other hand, the waveguide core is non-doping, and the loss due to free hole absorption can be neglected. Parameters such as the length and width of the taper, the electrode width, the electrode period, and the length from the taper to the first electrode were optimized by calculation shown in the inset of Fig. 1. As an example, Fig. 2(b) shows electrode period dependence of transmittance. The taper connected from the single-mode waveguide to the multi-mode waveguide is 5 μm length and 0.9 μm width. The calculated insertion loss of the phase shifter with 10 silicon electrodes is approximately 0.03 dB. In order to measure the designed phase shifter, We fabricated a structure with a phase shifter mounted on a ring resonator.

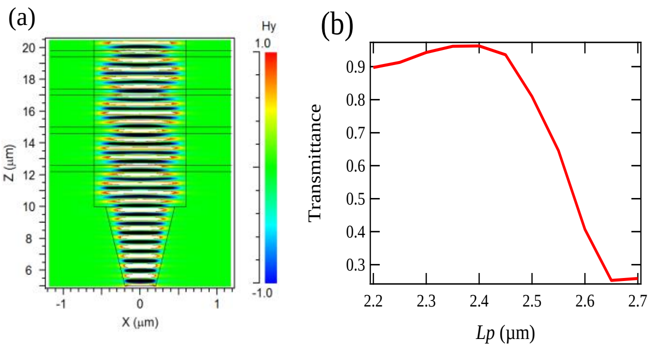

Fig. 2(a). Calculated mode field of MMI phase shifter.
(b). Electrode period dependence of transmittance.

3. Characterization of MMI phase shifter

The transmission spectrum of the ring resonator with phase shifter was measured. In order to obtain TE polarized light, the broadband light source was passed through the polarization controller and then incident on the ring resonator by the lensed-fiber. The laser light emitted from the lensed-fiber was split into a power meter and an optical spectrum analyzer by a 3 dB coupler. The measured resistance of the heater was 67 kΩ when the applying voltage was 10 V. Transmission spectrum of the drop port when changing the injection power to the electrode is shown in Fig. 3. Calculated heater power dependence of phase shift is shown in Fig. 4. We confirmed that the phase was linearly shifted by the input power. The heater injection power for π-phase shift was 13.1 mW. Therefore, we demonstrated the phase shift operation with the low power consumption.

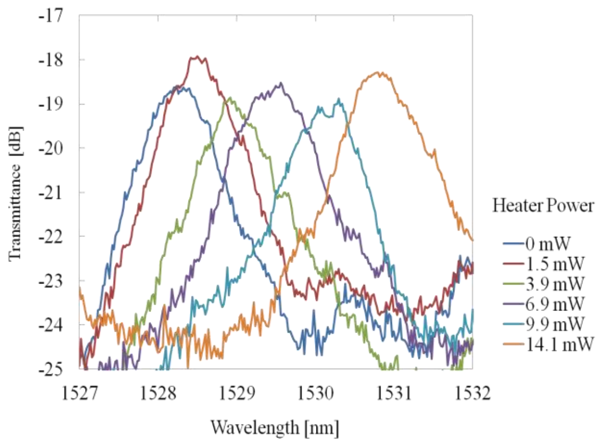

Fig. 3. Measured transmission spectra.

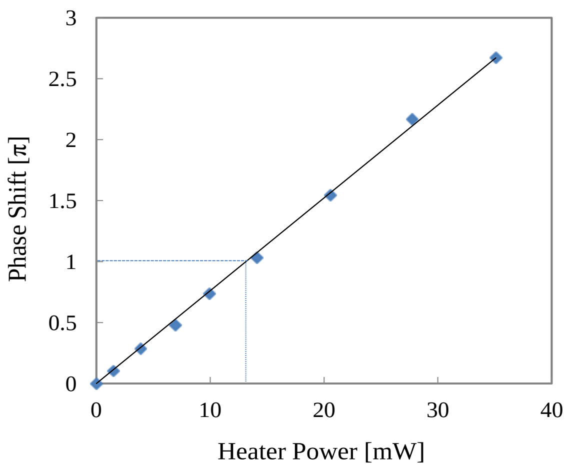

Fig. 4. Heater power dependence of phase shift.

Finally, the switching speed was measured with the measurement system as shown in Fig. 5. A laser beam having a resonance peak wavelength of 1542 nm was incident on the ring resonator loaded with phase shifter. The superposition of the temporal changes in the power applied to the heater and the light intensity detected by the photodetector is shown in Fig. 6(a) and Fig. 6(b). The heating time was defined as the time during the output light intensity attenuated to 10% of the maximum value. Similarly, the cooling time was defined as the time during the output light intensity reached to 90% of the maximum value. The time required for π-phase shift was about 7 μs at the time of heating and about 60 μs at the time of cooling.

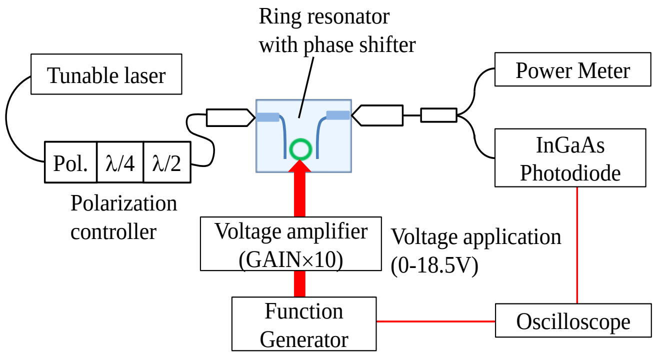

Fig. 5. Switching measurement system.

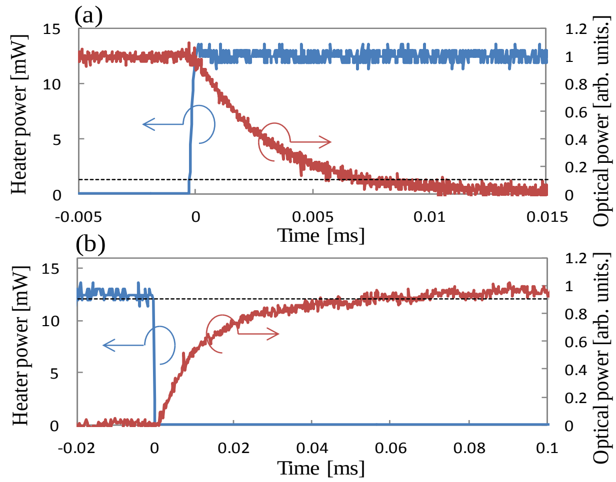

Fig. 6. Time-domain measurement of Optical Power.
(a). Heated (b). Cooled

4. Conclusions

We proposed and fabricated the phase shifter using multimode interference waveguide for optical switch of silicon-wire waveguide. By optimizing the heater structure, we demonstrated the low power consumption and high speed operation.

Acknowledgements

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References

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