Silicon Mach-Zehnder optical switch with an electric double layer phase shifter

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1. Introduction

Low power consumption optical switches with small footprints are desired for constructing integrated optical circuits used for various optical network devices and systems. Mach-Zehnder interferometer (MZI) optical switches and modulators with Si waveguides have been widely investigated for the purpose. In MZI devices, various types of phase shifters such as heaters utilizing thermo-optical effect [1], MOS capacitors [2,3] and p-i-n diodes utilizing carrier plasma effect [4] are studied.

On the other hand, electric double layer (EDL) transistors with electrolytes as gate dielectrics have been investigated in order to research various phenomena induced by high-density carrier accumulation such as electric field-induced superconductivity and electric field-induced ferromagnetism. EDL is formed by positive and negative charges separating with about 1 nm spacing. This is equivalent to a capacitor with 1 nm electrode gap. This applies strong electric field in the gap. Therefore, large change of carrier density is induced near the interface. It has been reported that sheet carrier density change of $10^{14}$ cm$^{-2}$ was achieved by EDL transistors made of ZnO, SnSe$_2$ or TiO$_2$ [5-7]. The large change of carrier density induces large change of refractive index through carrier plasma effect [8].

We proposed to apply the EDL as a phase shifter of MZI optical switches. Si-wire waveguide MZI optical switches with EDL phase shifters can realize small footprint and low switching voltage in spite of the simple structure. In this paper, we report fabrication of an optical switch with EDL phase shifters and measured the characteristics.

2. Structure of the EDL optical switch

The optical switch with an EDL phase shifter consists of an asymmetric MZI composed of p-type Si-wire waveguides with core cross-sectional size of 400×200 nm$^2$, a gate electrode which is connected to one of the arms of the MZI and ionic liquid (C$_5$H$_3$NOBF$_4$) which fill the MZI as shown in Fig. 1.

In the MZI, one of the arms near the gate electrode operates as a phase shifter, and the length of the phase shifter is about 100 μm. Another arm was 100 μm longer than the phase shifter. In order to isolate the phase shifter electrically from the other arm, directional couplers were used as optical couplers of the MZI.

Figure 2 shows the cross section of the EDL phase shifter. The operation of the switch is that when negative voltage is applied to the gate electrode, EDL made of hole and anion is formed at the Si/ionic liquid interfaces. And then, refractive index change is induced in Si through the carrier plasma effect. Therefore, optical output from the MZI can be modulated by applying gate voltage.

3. Measurement of the switching characteristics

We measured optical output spectra from the cross-port of the MZI for various applied gate voltages. In the measurement, TE polarized light from a LED light source with wavelength range of 1400~1600 nm was launched into fabricated optical switches. Figure 3 shows the output spectra measured for various gate voltages at the optical communication wavelength range of 1550 nm. Fringe pattern caused by optical interference in the MZI was observed in
the spectrum, and estimated visibility was about 6 dB.

The wavelength dependence of optical power output from the asymmetric MZI is given by the following equation,

\[ P = \cos^2 \left( \frac{n_{\text{eff}} \pi \Delta L}{\lambda} \right) \]  

(1)

Here, \( n_{\text{eff}} \) is effective refractive index, \( \Delta L \) is path difference of two MZI arms. Next, we normalized these measured data by maximum values for each gate voltage within the wavelength range of 1545–1560 nm and fitted them to the equation (1) in order to estimate free-spectrum-range (FSR) and peak wavelength shift. And then, we plotted phase shifts for absolute value of gate voltage by using the following equation,

\[ \Delta \phi = 2\pi \frac{\Delta \lambda}{\text{FSR}} \]  

(2)

Here, \( \Delta \phi \) is the phase shift induced by applying voltage, and \( \Delta \lambda \) is peak wavelength shift. Figure 4 shows the phase shift plotted against absolute value of gate voltage, and the linear fitting. From this figure, we estimated voltage required for \( \pi \)-shift (\( V_\pi \)) as 18 V. Since length of the phase shifter (\( L_e \)) was 100 \( \mu \)m, we estimated the figure of merit \( V L_e \) as 0.18 V cm. This figure of merit value \( V L_e \) is nearly three times smaller than that achieved in conventional MZI optical modulator with MOS capacitor phase shifter (0.5 \( \sim \)0.67 V cm) [3].

4. Conclusions

We proposed an MZI optical switch with Si waveguides and EDL phase shifter, and fabricated the device to measure the optical properties. We measured the visibility of about 6 dB from the output spectra, and estimated the figure of merit of \( V L_e \) \( \sim \)0.18 V cm. Although the value of the visibility needs to be improved for practical use as switching devices, the value of the figure of merit is more improved than that of conventional MZI with MOS capacitor phase shifter. We showed the attractive characteristics of EDL as phase shifter of MZI optical switch to realize low switching voltage and small footprint.

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References