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Low-Crosstalk Optical Switch with InGaAsP/Si Hybrid MOS Optical Phase Shifter

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Abstract

In this study, we proposed an optical switch based on an InGaAsP/Si hybrid MOS optical phase shifter. The numerical analysis revealed that low-crosstalk switching can be obtained owing to the large electron-induced refractive index change with the small absorption. The minimal achievable crosstalk was predicted to be approximately -38 dB, exhibiting the great potential in the application of optical routing and switching.

1. Introduction

An optical switch is expected to be a fundamental building block for optical interconnect system. In addition to the thermo-optic effect, the free-carrier plasma dispersion effect is the most commonly used mechanism in Si photonics for optical phase modulation. However, the coexisting free-carrier absorption enormously deteriorates the crosstalk and insertion loss of Si optical switch. High-port-count Si optical switch fabrics, such as 16×16 [1], 8×8 [2,3] and 4×4 [4,5], have been demonstrated, while the large crosstalk of -20~-30 dB prohibits their further scalability and application in larger scale switch fabrics. A crosstalk lower than -35 dB is required in order to obtain proper system performance for switch arrays [6].

In previous study, we have demonstrated an InGaAsP/Si hybrid metal-oxide-semiconductor (MOS) phase shifter experimentally by using direct wafer bonding [7, 8]. Owing to the large electron-induced refractive index change in InGaAsP, the hybrid phase shifter showed an extremely low $V_{\pi}L$ of 0.05 Vcm, which implies its application in optical switch. In this study, we explored the potential of InGaAsP/Si hybrid MOS optical phase shifter in the reduction of crosstalk for Mach-Zehnder interferometer (MZI) optical switch.

2. Result and Discussion

Figure 1(a) shows a schematic of a proposed Mach-Zehnder interferometer (MZI) optical switch consisting of two ideal 3-dB couplers and two InGaAsP/Si hybrid MOS optical phase shifters on the MZI arms. Figure 1(b) presents a cross-sectional schematic of the InGaAsP/Si hybrid MOS optical phase shifter, in which an n-type InGaAsP layer is bonded on a p-type Si waveguide. When a gate voltage is applied between the InGaAsP and Si layers, electrons accumulate at the InGaAsP MOS interface, resulting in phase modulation. Figure 1(c) is a typical switching characteristic of an MZI optical switch. We define the crosstalk by the output power ratio of Port 1 and 2 at the bar state.

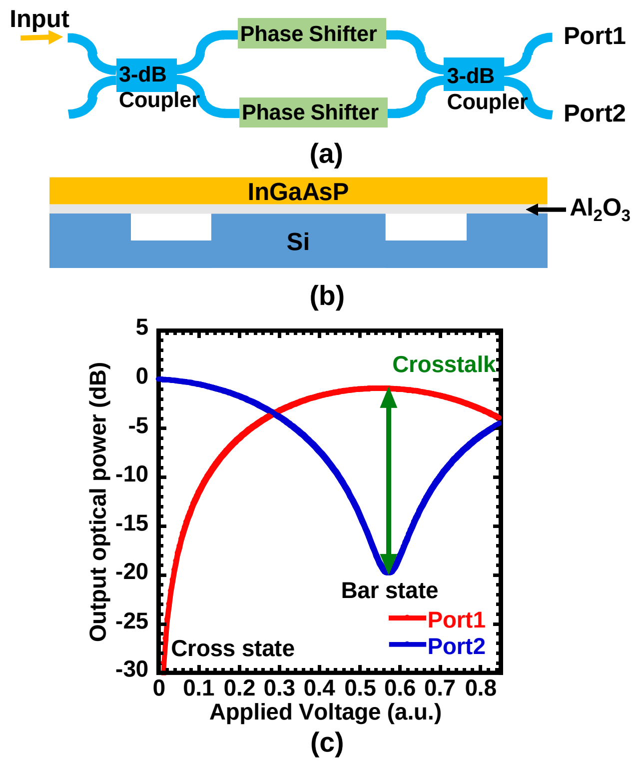


Fig. 1 (a) Schematic of MZI optical switch, (b) cross-section of InGaAsP/Si hybrid MOS optical phase shifter, and (c) crosstalk at bar state of MZI optical switch.

To evaluate the crosstalk, we numerically analyzed the switching characteristics of MZI optical switch by using the transfer matrix method. The transfer matrix of a 3-dB coupler is given by

$$C = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix}. \quad (1)$$

The transfer matrix of the phase shifter can be expressed by

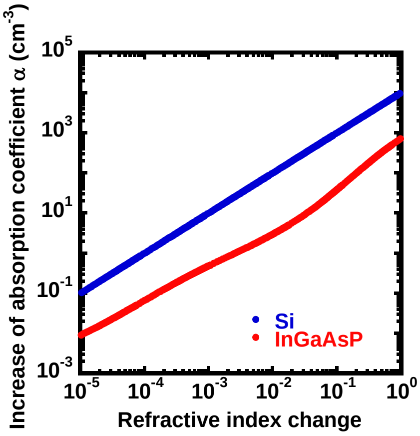
$$P = \begin{bmatrix} 1 & 0 \\ 0 & e^{-j\Delta\beta_1 L} \end{bmatrix}, \quad (2)$$

with $\Delta\beta_1$ being the change in the propagation constant of one of the phase shifters, and L being the length of the phase shifter. The change of propagation constant is

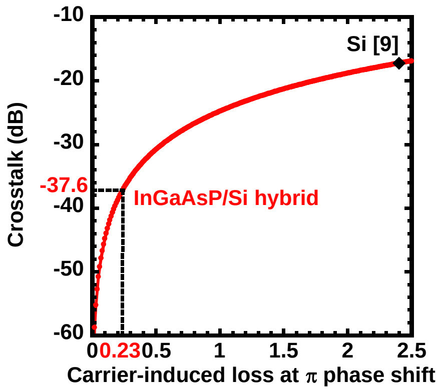
$$\Delta\beta_1 = \frac{2\pi}{\lambda}\Delta n - j\frac{\Delta\alpha}{2} \quad (3)$$

where Δn and $\Delta\alpha$ are the change in effective refractive index and absorption coefficient induced by the accumulated carriers, respectively. The total transfer matrix of the MZI optical switch is

$$T = CPC = \frac{1}{2}\begin{bmatrix} 1 - e^{-j\Delta\beta_1 L} & j\left(1 + e^{-j\Delta\beta_1 L}\right) \\ j\left(1 + e^{-j\Delta\beta_1 L}\right) & -1 + e^{-j\Delta\beta_1 L} \end{bmatrix}. \quad (4)$$



(a)



(b)

Fig. 2 (a) The relationship between the changes in refractive index and absorption coefficient and (b) the relationship between the carrier-induced absorption loss at π phase shift and the crosstalk of the optical switch.

We first numerically estimated the electron-induced effects in InGaAsP. Figure 2(a) exhibits the relationship between the electron-induced changes in refractive index and absorption coefficient in Si and InGaAsP. Since InGaAsP has significantly greater refractive index change than Si, for the same change of refractive index, the increase in absorption coefficient in InGaAsP is 10~30 times smaller than that in Si. Figure 2(b) illustrates the relationship between the carrier-induced absorption loss at π phase shift and the minimal achievable crosstalk obtained by using the transfer matrix. It is apparent that the minimal achievable crosstalk is limited by the carrier-induced absorption loss, because it causes the optical power imbalance between the two arms of the MZI. For the Si phase shifter based on a Si MOS structure demonstrated by CISCO [9], a loss of 2.4 dB was reported at π phase shift, which means the crosstalk will be limited above -20 dB. In comparison, the ultra-low carrier-induced absorption loss of 0.23 dB at π phase shift is expected in the InGaAsP/Si hybrid MOS optical phase shifter when the phase shifter length is assumed to be 500 μm, enabling a crosstalk of -37.6 dB.

The switching characteristics of the MZI optical switch based on the InGaAsP/Si hybrid MOS optical phase shifter is plotted in Fig. 3. The equivalent oxide thickness (EOT) of the gate oxide was assumed to be 5 nm. By applying the gate

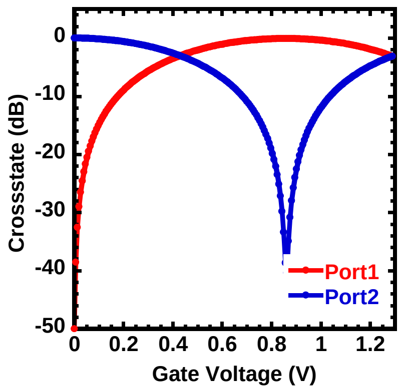


Fig. 3 The switching characteristics of MZI optical switch based on the InGaAsP/Si hybrid MOS optical phase shifer.

voltage, the accumulated electrons at the InGaAsP MOS interface induces the large change in the refractive index, resulting in switching from the cross state to the bar state. The switching voltage was predicted to be 0.86 V. Since the gate leakage current is negligible, the switching power could be dramatically reduced as compared with a thermo-optic switch. As discussed in Fig. 2(b), the low crosstalk of -37.6 dB is achieved owing to the small electron-induced absorption in InGaAsP.

3. Conclusions

We proposed an MZI optical switch based on an InGaAsP/Si hybrid MOS optical phase shifter. The numerical analysis revealed that the proposed optical switch exhibited low crosstalk of -37.6 dB owing to accumulated electrons at the InGaAsP MOS interface which induced large refractive index change with relatively small absorption. This study indicated the great potential of InGaAsP/Si hybrid MOS optical phase shifter for low-crosstalk and low-power optical switches.

Acknowledgements

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