Silicon thermo-optic variable optical attenuators based on Mach–Zehnder interference structures

Qianqian Wu a, Linjie Zhou a,*, Xiaomeng Sun b, Haikuo Zhu a, Liangjun Lu a, Jianping Chen a

a The State Key Laboratory of Advanced Optical Communication Systems and Network, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
b Technische Universitat Berlin, Fachgebiet Hochfrequenztechnik, Einsteinufer 25, 10587 Berlin, Germany

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Abstract

We experimentally demonstrate silicon variable optical attenuators (VOAs) based on thermally tunable Mach–Zehnder interferometers (MZIs). Thermo-optic tuning is enabled by a silicon resistive micro-heater positioned beside the MZI arm. Experimental results reveal that the maximum attenuation is around 30 dB with 50 mW power consumption. Compared with the p–i–n diode based VOA, the MZI-VOA is more power efficient and compact. The influence of MZI arm length on the performance of MZI-VOA is also investigated. The maximum attenuation voltage for the MZI-VOA with a 50 μm long arm length is around 6.6 V.

1. Introduction

In modern optical networks, variable optical attenuator (VOA) is a basic component and plays an essential role in a wide range of applications in optical communications especially for channel power equalizing in wavelength division multiplex (WDM) technologies [1,2]. There are many implementations of VOAs in the literature, such as microfluidics [3], planar light wave circuits [4,5], microelectromechanical systems [6,7], and tunable silicon photonics devices [8] etc.

As implementation of VOAs in photonic integrated circuits (PICs) demands compact size, low power consumption, and compatible fabrication with other photonic devices, the VOAs made of silicon photonics are especially attractive. They are compatible with standard complementary metal-oxide-semiconductor (CMOS) processes and can be highly integrated due to the high refractive index contrast between silicon and silica. Silicon VOAs can be realized based on the free-carrier absorption effect using p–i–n diodes [9,10] or the thermo-optic effect using coupling or interference structures [11]. Limited by the saturated free carrier concentration, the maximum attenuation of p–i–n type VOA depends on its length, and thereby high attenuation is difficult to achieve in a short device length.

Due to the relatively large thermo-optic coefficient of silicon, VOAs based on thermo-optic effect have also received much attention. A thermo-optic VOA consisting of three cascaded three-waveguide directional couplers has been reported [12], but this structure is 2.6-cm-long and 200-μm-wide, and the fabrication is relatively complex for Al₂O₃ layers. Mach–Zehnder Interferometers (MZIs) composed of two 3-dB couplers have more compact size and become a popular choice. In this structure, the phase difference between the two arms induced by a heater is translated into intensity modulation at the output port. For broadband operation, the two arms of MZIs are usually of equal length.

In previously demonstrated MZI-VOAs, thin film heaters (e.g. Titanium) positioned on top of the MZI arms are widely used. Such an arrangement of heaters is not power efficient. Even with isolating grooves, power consumption still reaches 140 mW for attenuation of 29 dB on the silicon-on-insulator (SOI) platform [13] and 180 mW for attenuation of 30 dB on the quartz substrate by simulation [14]. Moreover, these metal heaters require an additional fabrication step for the metal layer. More efficient heaters for thermo-optic tuning in various structures have been reported [15]. A lateral p–i–p junction can be used as a micro-heater with high power efficiency and fast response speed [16]. In this paper, we report a silicon MZI-VOA with its tuning enabled by a resistive micro-heater formed by a highly doped silicon slab outside the active MZI arm. The experimental result shows our VOA can have the maximum attenuation of 30 dB at 50 mW power consumption.

2. Device structure and fabrication

Fig. 1(a) shows the schematic structure of our MZI-VOA. The silicon ridge waveguide is 500-nm-wide and 220-nm-thick with a...
60-nm-thick slab. The slabs outside the MZI arms are highly n-type doped with a doping density of $10^{20}$ cm$^{-3}$. The separation distance of the doping region from the waveguide edge is 1 μm. The cross section of the active arm is depicted in the inset. When current flows through the resistor formed by the doped slab, heat will be generated and diffuse to interact with the nearby waveguide, thereby raising its temperature. Due to the thermo-optic effect of silicon, the waveguide effective refractive index changes, leading to a phase shift. In order to reduce the thermal crosstalk between the two MZI arms, 10-μm-wide trenches are etched down into the silicon substrate to isolate the heater so as to increase the power efficiency.

The optical power attenuation is resulted from the interference between the two MZI arms. The normalized optical power transmission in dB unit can be derived as follows:

$$T(dB) = 10 \log \left( \frac{P_{out}}{P_{in}} \right) = 10 \log \left( \frac{1}{2} (1 + \cos(\Delta \phi)) \right).$$

(1)

where $\Delta \phi$ is the phase difference between the two arms. In the range of $0 \leq \Delta \phi \leq \pi$, $T$ is inversely proportional to $\Delta \phi$.

In comparison, we also characterize a reference VOA composed of a straight silicon waveguide embedded with a lateral p–i–n diode. The waveguide has the same dimensions with that of the MZI-VOA. The separation distance of the n$^+$ and p$^+$ doping regions from the waveguide edge is 0.8 μm. The doping densities are both $10^{20}$ cm$^{-3}$. When a voltage is applied on the p–i–n diode, free carriers are injected into the waveguide, leading to absorption loss.

Our devices were fabricated on a silicon-on-insulator (SOI) wafer using the standard CMOS fabrication process. 248-nm deep ultra-violet (DUV) photolithography and plasma dry etch were used to pattern the waveguides with an etched depth of ~160 nm. Then, phosphorus and boron ion implantations were performed to form the resistors and p–i–n diodes. Plasma-enhanced chemical vapor deposition (PECVD) was used to deposit a 1.5-μm-thick silicon

![Fig. 1.](image1.png) *(a) Schematic illustration of our MZI-VOA. Inset: cross-sectional structure of the active arm. (b) Microscope image of the MZI-VOA.*

![Fig. 2.](image2.png) *(a) Simulated cross-sectional temperature distribution in the active MZI arm. (b) Effective refractive index change and phase shift versus power consumption. (c) Optical transmission versus power consumption.*
dioxide layer. After the contact holes were etched through the oxide layer, an aluminum layer was sputtering deposited to form ohmic contact with the highly doped slab regions. The aluminum layer was then patterned for metal connection. Finally, trenches were etched deep down into the silicon substrate (∼100 μm deep) using inductively coupled plasma (ICP) etching to isolate the micro-heaters.

3. Simulation

We first simulated the temperature distribution in the phase shifter composed of a silicon waveguide and a resistive micro-heater using the Joule Heating module from COMSOL. The temperature at the bottom of the silicon substrate is fixed at the room temperature. Thermal isolation boundary condition is applied to the other boundaries. Fig. 2(a) shows the temperature rise at the cross-section of the phase shifter when 6.5 mA current flows through the resistor. The power consumption is 36 mW for a 50 μm long arm. It reveals that the slab (heating source) has the highest temperature rise of 129 °C, while the waveguide has slightly lower temperature rise of 83 °C. The temperature has a fast

Fig. 3. Simulated effective refractive index (real and imaginary parts) change with voltage in a p-i-n diode integrated waveguide. Inset: waveguide propagation loss as a function of voltage.

Fig. 4. Measured transmission spectrum evolution with voltage for (a) 50 μm MZI-VOA, (b) 100 μm MZI-VOA, (c) 150 μm MZI-VOA, (d) 200 μm MZI-VOA, and (e) p-i-n type VOA.
drop in the buried oxide layer due to the good thermal conductivity of silicon substrate, which lowers the power efficiency in heating up the waveguide.

With the temperature distribution, we obtained the waveguide effective refractive index change $\Delta n_{\text{eff}}$ by using the Wave Optics module from COMSOL. The thermo-optic coefficient of silicon is set as $1.84 \times 10^{-4}$ K$^{-1}$ and silica $1.0 \times 10^{-5}$ K$^{-1}$. Fig. 2(b) shows the simulated effective refractive index variation and phase shift as a function of power consumption. The phase shift is given by

$$\Delta \phi = \frac{2\pi}{\lambda} \Delta n_{\text{eff}} L.$$  (2)

where $\lambda = 1.55 \mu m$ is the wavelength and $L = 50 \mu m$ is the arm length. The phase shift is linearly proportional to the effective refractive index change. The optical power transmission can be obtained from (1) as shown in Fig. 2(c). The maximum attenuation is achieved at the power consumption of $\sim 36$ mW. It should be noted that although the trenches can effectively prevent heat lateral diffusion, there is still significant heat leakage into the silicon substrate as seen from Fig. 2(a). The power efficiency can be further improved if the silicon substrate is removed as demonstrated in [17].

We next simulated the $p-i-n$ type VOA. Silvaco is used to simulate the electron and hole distribution in the intrinsic region when a forward bias is applied to the $p-i-n$ diode. The electron and hole distribution was then input to the Wave Optics module from COMSOL to simulate the waveguide effective refractive index. The injection of free carriers changes both the real ($\Delta n$) and imaginary ($\Delta k$) parts of the silicon refractive index. At 1550 nm, the refractive index change is given by [18]

$$\Delta n = - \left( 8.8 \times 10^{-22} \times \Delta N_e + 8.5 \times 10^{-18} \times \Delta N_h \right)$$  (3)

$$\Delta k = \frac{\lambda}{4 \pi} \left( 8.5 \times 10^{-18} \times \Delta N_e + 6.0 \times 10^{-18} \times \Delta N_h \right)$$  (4)

where $\Delta N_e$ and $\Delta N_h$ are changes of electron and hole concentrations, respectively. Fig. 3 shows the waveguide effective refractive index change with the applied voltage on $p-i-n$ diode. The waveguide propagation loss versus voltage is shown in the inset. The optical power attenuation is quite sensitive to voltage once the $p-i-n$ diode is turned on. The attenuation of the $p-i-n$ type VOA is linearly proportional to the waveguide length.

4. Experiments

In order to investigate the effect of MZI length on VOA performance, we fabricated four MZI-VOAs with arm lengths of 50 $\mu m$, 100 $\mu m$, 150 $\mu m$, and 200 $\mu m$. To tune the attenuation, one of the MZI arms was connected to an external voltage source while an ampere meter simultaneously monitored current. We measured the transmission spectrum at various voltages. Fig. 4(a)–(d) shows the transmission spectra of the MZI-VOAs with arm lengths of 50 $\mu m$ to 200 $\mu m$. The attenuation increases with voltage for each MZI-VOA and the 50 $\mu m$ long MZI-VOA reaches its maximum attenuation at only 6.6 V. It can be seen that MZI-VOAs of different lengths have similar attenuation trend with voltage but the voltage required to achieve the maximum attenuation increases with arm length. As grating couplers are used in our devices, the transmission spectrum has a Gaussian-like envelope centered around 1.57 $\mu m$. The minimum coupling loss is approximately 5.8 dB per facet. This coupling efficiency can be improved by optimizing the grating coupler as demonstrated in Ref. [19]. The small fluctuation fringe in the spectrum is due to the Fabry–Perot resonances formed by the two grating couplers. The large fluctuation that is more severe at high attenuation is resulted from the interference between the wave transmission through the device and that directly reflected at the device surface to the output fiber (the input and output fibers are close to each other with a lateral distance of $\sim 1 \text{ mm}$).

We also characterized the reference $p-i-n$ type VOA with its transmission spectra shown in Fig. 4(e). The waveguide length is 200 $\mu m$, four times longer than the MZI-VOA in Fig. 4(a). The maximum attenuation is 10 dB reached at 2.2 V. After 2.2 V, the free carrier concentration saturates and the attenuation cannot be further increased. The attenuation range can be enlarged by increasing the carrier lifetime as proposed in Ref. [20].

To compare MZI-VOAs with different arm lengths, Fig. 5(a) shows the normalized optical power transmission as a function of voltage for the four MZI-VOAs together with the reference device. The optical power is averaged in the wavelength range of 1540–1560 nm to eliminate the influence of the fringes on the spectrum. The maximum attenuation of the four MZI-VOAs all can reach $\sim 30$ dB. The voltage at the maximum attenuation $V_{\text{fl}}$ (corresponding to $\pi$-phase shift of the active arm) varies with the MZI length. Although the operation voltage of the MZI-VOAs is higher than that of the $p-i-n$ type VOA, they can achieve higher attenuation. Moreover, they are also less sensitive to voltage variation in the low attenuation region. Fig. 5(b) shows the relationship between the optical transmission and the power consumption. The

Fig. 5. Transmission varies as a function of (a) voltage and (b) power consumption for the four MZI-VOAs and the reference $p-i-n$ type VOA.
maximum attenuation is achieved with 50 mW power consumption for all four MZI-VOAs. This value is higher than the simulation, which is probably because our simulation is two-dimensional without taking into consideration the influence of heater end facets and metal connections where strong heat leakage takes place.

Although it does not improve the power efficiency by reducing the MZI arm length, the operation voltage can be reduced with a shorter arm (see Fig. 5(a)). It should be noted that the temperature cannot be too high because that would lead to stability issues or even destroy the device. The temperature rise is 129 °C for the 50 μm MZI-VOA. If the length is reduced to 30 μm, the temperature rise would be as high as 207 °C.

As a comparison, the performance of the p- i- n type VOA is also depicted in Fig. 5(b). Although only 2.2 V is enough to achieve 10 dB attenuation, the power consumption is around 100 mW (~50 mA current), which is much larger than that of MZI-VOAs.

5. Conclusion

We have demonstrated compact and efficient MZI-VOAs tunable by integrated micro-heaters made of highly doped thin slabs beside the waveguide. Experimental results reveal that a maximum attenuation of 30 dB is achieved with 50 mW power consumption. The operation voltage is dependent on the MZI length and the 50 μm long MZI-VOA has a maximum attenuation voltage of 6.6 V. The power efficiency of the MZI-VOAs can be further improved by removing the silicon substrate to isolate the resistive heater. Compared with p- i- n type VOAs, the MZI-VOAs are shorter in length and more efficient in power consumption.

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