

Silicon Nanowire-Based Thermo-Optical Tunable Reflector

Junfeng Song, Xianshu Luo, Xiaoguang Tu, Lianxi Jia, Tsung-Yang Liow, Mingbin Yu, and Guo-Qiang Lo

Abstract—We propose and demonstrate a Mach-Zehnder interferometer associated waveguide loop mirror for tunable reflectors in silicon substrate. Experiments show that the transmissivity and reflectivity can be tuned between 0.01 and 0.98 via thermo-optical effect. The tuning energy is ~ 9 mW and 10%-90% tuning time of ~ 5.4 μ s. Such tunable reflector can be used for hybrid Si laser cavity with tunable mirror reflection.

Index Terms—Thermo-optical effect, optical switch, silicon photonics, integrated photonics

I. INTRODUCTION

Silicon photonics using silicon-on-insulator have been attracting more and more research interests [1]-[3]. Thanks for the high index contrast. It enables silicon photonic devices with compact footprint, and compatible with CMOS technology. Silicon based devices, such as AWG[4-5], interleaver [6]-[8], optical switch [9]-[10], modulator and photodetector [11], and subsystems, such as, ROADM [12]-[13], WSS [13] are reported in succession. However, due to the indirect band gap of Si, it is difficult to realize optical light source in Si platform. Thus by means of III-V materials bonding technology, hybrid lasers are demonstrated by several research groups [14]-[15].

Optical cavity is the one of the basic element for laser emission in order for increasing the photon's life time and reducing the modes number in cavity. Generally, laser cavities are made of two mirrors with different kinds of structures, including Fabry-Perot cavity by index difference between semiconductor and air [14], distribution Bragg reflector (DBR) [16], micro-ring/micro-disk [17], and so on. However, almost all of these cavities are fixed after fabrication, which limits the optical laser properties and applications.

In this paper, we propose and demonstrate a Mach-Zehnder interferometer (MZI) associated waveguide loop structure for tunable reflectors in silicon substrate. By integrating the thermal heater to the MZI arms for

thermo-optical tuning, the loop mirror transmissivity and reflectivity can be tuned between 0.01 and 0.98. The measured tuning energy is ~ 9 mW with 10%-90% tuning time of ~ 5.4 μ s.

II. DESIGNATION, FABRICATION, AND CHARACTERIZATIONS

A. Designation

Fig. 1(a) shows the schematic of a silicon nanowire-based loop mirror, which comprises a 2×2 directional coupler (DC) connecting to a waveguide loop, and two of output waveguides. The reflectivity and transmissivity are $4\kappa^2 t^2$ and $(t^2 - \kappa^2)^2$. Where t and κ are the self- and cross- coupling coefficients of the directional coupler. Based on the basic element, we adjusted the design with the DC replacing by a MZI structure and integrating thermal heater to the two MZI arms in order for thermo-optical tunability. Figure 1(b) shows the MZI-associated loop mirror.

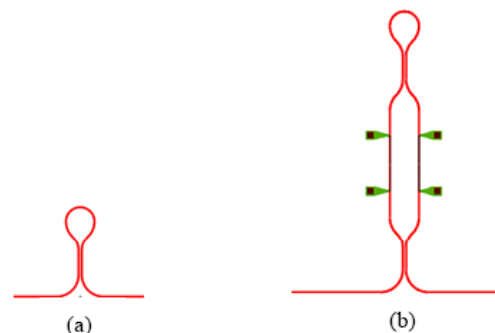


Fig. 1. (a). The basic element of a loop mirror. (b). Tunable MZI-associated loop mirror. Red color lines denote the waveguides.

By simple deduction, we can obtain the power reflection and transmission coefficient of the MZI-associated loop mirror as

$$\begin{aligned} R &= 4\kappa^2 t^2 |P|^2 (1 - \kappa^2 t^2 |P|^2) \\ T &= (1 - 2\kappa^2 t^2 |P|^2)^2 \end{aligned} \quad (1)$$

where, $|P|^2 = 2[1 + \cos(\Delta\theta)]$, and $\Delta\theta$ is the phase difference between two MZI arms. The contour maps of the reflectivity and transmissivity according to the variation of the phase different and the DC transmission coefficient are shown in Fig. 2(a) and (b). We observe that the reflectivity and the transmissivity are complementary and periodic functions to the phase difference with a period of 2π . However when t^2 closes to 0.5, the transmissivity and reflectivity are close to

Manuscript received July 6, 2012; revised August 25, 2012.

This work was partially supported by the program for New Century Excellent Talents in University (NCETU), Nature Science Funding of China, NSFC (61177090), and Science and Engineering Research Council of A*STAR (Agency for Science, Technology and Research), Singapore under SERC grant number 1122804038.

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$\cos^2(\Delta\theta)$ and $\sin^2(\Delta\theta)$, with a period of π . From the point view of switch function, the phase change for on/off states reduces half period.

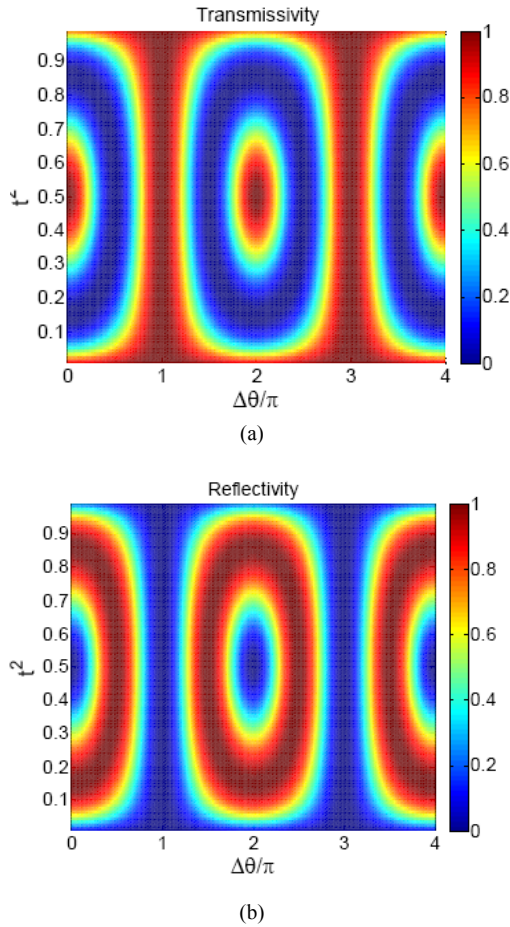


Fig. 2. Transmissivity and reflectivity as function of square of self coupling coefficient and phase difference.

B. Fabrication

We fabricate the proposed MZI-associated loop mirror in 200-mm SOI with 220 nm thick top silicon and 2 μm -thick buried oxides using CMOS-compatible fabrication process. Firstly, we deposit 70 nm undoped silicate glass oxide (USG) as the hard mask, followed with waveguide patterning by 248 nm deep UV photolithography. The Si waveguide is formed by plasma reactive ion etching (RIE) process. Spot size converters (SSCs) are fabricated at the input and output coupling facets in order to reduce the coupling losses between fiber to waveguide and vice versa. These SSCs are nano-tapers with 200 nm-wide tips and 200 μm in length. Then $\sim 1.5 \mu\text{m}$ high-density plasma (HDP) oxide is deposited, followed by 150 nm Titanium nitride (TiN) deposition for the thermal heater. A 50 nm-thick silicon nitride is deposited for TiN etching stop layer. After the formation of contact holes, $\sim 750 \text{ nm}$ thick aluminum is deposited, followed by metal pad etching. Finally, the deep trench is etched by ICP in order for ease fiber coupling.

Fig. 3 shows the optical microscope of the fabricated device. The waveguide is designed with 400 nm. The input and output DCs are with length and gap of 11 μm and 300 nm, respectively. The radius of the waveguide loop is 12.5 μm . The length of the MZI arms are 100 μm and the length of thermal heaters are 74 μm .

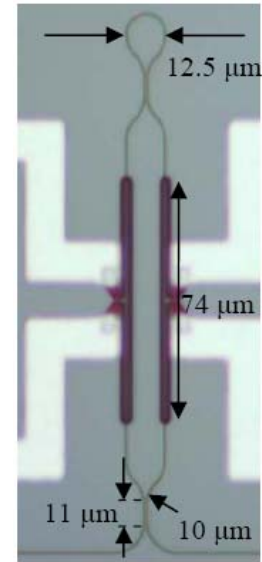


Fig. 3. Optical microscope of the fabricated MZI-associated thermo-optical tunable loop mirror.

C. Characterizations

Fig. 4 shows the measurement setup. A laser light source at wavelength of 1550 nm, passing through a polarization controller and a circulator, is set as the light source before entering the device. The transmission is measured from port A while the reflection is measured from port B via the circulator. Thus, the transmissivity and reflectivity can be normalized via the following equations, where A and B represent the optical power measured from ports A and B, respectively.

$$\begin{cases} R = \frac{B}{A+B} \\ T = \frac{A}{A+B} \end{cases} \quad (2)$$

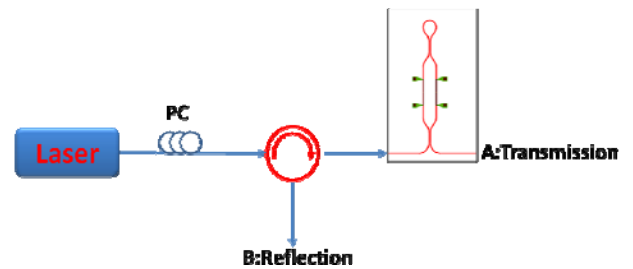


Fig. 4. Schematic of the measurement setup.

Fig. 5 shows the measured transmissivity and the reflectivity as functions of the electrical powers to one of the MZI arms. The measured transmissivity and reflectivity range from 0.98 to 0.01 with periodicity. The period for one cycle is with a power consumption of $\sim 9 \text{ mW}$. The power consumption is similar to the Michelson Interferometer optical switch[9]. As the light transmission via the MZI arm twice, the required phase change is reduced half, thus the power consumption.

We also measured the optical response of the tunable loop mirror in order to investigate the tunable speed via inputting a 10 kHz square wave driving voltage to one of the MZI arm and measure the optical response from the transmission port (port A). Fig. 5(b) shows the measured optical response with

the yellow line the input square wave signal. The rise time and fall time are 5.4 μ s and 5.2 μ s, respectively, corresponding to a tuning speed of 100 kHz.

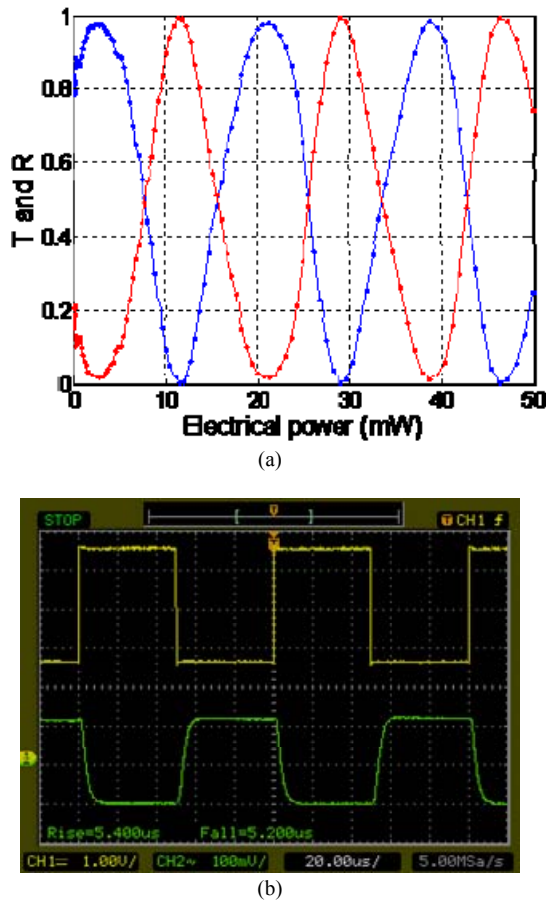


Fig. 5. (a) Measured transmissivity and reflectivity. Blue- and red-line denote the transmissivity and reflectivity, respectively. (b) Optical response measurement. Rise time and fall time are 5.4 μ s and 5.2 μ s, respectively.

III. DISCUSSION AND CONCLUSION

We propose and demonstrate a MZI-associated loop mirror working as tunable reflector. Transmissivity and reflectivity range from 0.01 to 0.98 are obtained via thermo-optical tunability. The switching power for one period change from 0.01 to 0.98 is measured to be 9 mW with tuning speed of 5.4 μ s. Such tunable loop mirror is applicable hybrid Si laser as tunable mirror for Q-switch laser and mode locking laser.

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