Design of Silicon Photonic Mode-Sensitive Thermo-Optic Phase Shifter based on Subwavelength Grating Structures

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***Abstract*—We present a mode sensitive thermo-optic phase shifter for applications in multi-transverse-mode optical processors and mode division multiplexing systems. The design is based on subwavelength grating structures offering 2.2 times differential thermo-optic coefficient between the first two transverse electric (TE) modes.**

Keywords—Silicon Photonics, Subwavelength Grating, Thermo-optic Phase Shifter, Multimode Silicon Photonics.

I. Introduction

Multimode Silicon Photonics (SiPh) have been widely used in mode division multiplexing (MDM) systems employing higher order transverse electric (TE) and transverse magnetic (TM) spatial modes [1]. Recently, we have proposed a multi-transverse-mode optical processors (MTMOPs) enabling on-chip monitoring of phase shifters towards realizing a programmable optical processor with fully integrated programming units [2]. Different building block components are required for that kind of integrated system and other multimode SiPh systems, such as a mode multiplexer/demultiplexer, mode exchanger, and multimode thermo-optic phase shifter (TOPS).

The multimode TOPS can be either *mode-insensitive* or *mode sensitive*. We have already shown *mode-insensitive* operation of a 4 µm wide TOPS for the first three TE modes [3]. This TOPS is used in mode-insensitive MDM switches where we require similar performance of the component for all TE modes. However, in other applications, we require for *mode-sensitive* performance of TOPS. For example, the MTMOP needs phase shifters offering wide different thermo-optic coefficients for TE0 and TE1 [2]. In addition, a mode-sensitive TOPS would be beneficial to MDM switches as well where routing a specific mode to a desired port is needed. Previously, we showed mode-sensitive operation of a narrow multimode TOPS with a width smaller than 1 µm [2, 3]. However, the mode sensitivity of this TOPS is relatively poor resulting in less than 1.1 times difference in the thermo-optic coefficient for TE0 and for TE1 (1.8 and 1.96 for TE0 and TE1, respectively.) In this work, we design a mode-sensitive TOPS offering 2.2 times different thermo-optic coefficient between the first two transverse electric (TE) modes. The design relies on the fact that the fundamental mode (TE0) propagates mainly in the multimode waveguide center whereas the first order mode (TE1) field pattern exhibits two lobes closer to the waveguide sidewalls. The thermo-optic coefficient of silicon is an order of magnitude larger than that of oxide. By engineering the thermo-optic coefficient of the regions closer to the waveguide sidewalls using sub-wavelength grating (SWG) structures while keeping the waveguide center as silicon, we realize wide different thermo-optic coefficient for TE0 and TE1.

II. Design and Discussion

Figure 1(a) shows the mode-sensitive TOPS design structure. The TOPS consists of a 500 nm silicon core for TE0 propagation. On the two waveguide sides, SWG structures with a duty ratio of *f* guides the two lobes of the second order mode (TE1).

$$f = {L_{Si}}/{(L_{Si} + L_{Oxide})} \qquad (1)$$

In the above equation, L_{Oxide} is the length of the etched silicon part filled with SiO_2 cladding, and L_{Si} is the length of the un-etched remaining silicon. We design the mode-sensitive TOPS to be fabricated at the Applied Nanotool (ANT) foundry. The silicon layer thickness is 220 nm. A 200 nm thick Titanium Tungsten (TiW) metal heater is deposited on top of the 2.2 µm oxide cladding. The TiW heater is sufficiently wide (3 µm) to provide uniform heating. The pitch of the SWG structure ($\Lambda = L_{Si} + L_{Oxide}$) remains small enough to ensure the SWG structure is in the subwavelength regime [4] to avoid Brag reflection. We use a 2.5-D simulation approach in which we reduce the 3-D original structure to 2-D by considering an effective refractive index for the SWG structure. For a TE polarization beam with a major electric component parallel to the optical axis, the effective refractive index of the SWG structure is the following [4],

$$n_{SWG} = [f n_{si}^{-2} + (1-f) n_{oxide}^{-2}]^{-0.5} \qquad (2)$$

where, $n_{Si} = 3.46$ and $n_{oxide} = 1.45$ are the material indices of silicon and SiO_2, respectively. We then use a 2-D commercially available Finite-Difference Eigenmode (FDE) Lumerical mode solver to calculate the effective refractive index (n_{eff}) of the TOPS for TE0 and TE1. We calculate the thermo-optic coefficient (d_{neff}/dT) of the TOPS by adding the thermo-optic coefficient of 1.86×10^{-4} K^{-1}, and

$0.95{\times}10^{-5}$ K^{-1}, to silicon and SiO_2 material index, respectively [5]. Considering the fact that the TE0 main lobe is mainly situated in the silicon core and the two lobes of TE1 are in the SWG structure (see Fig. 1[b]), the large difference between the thermo-optic coefficient of silicon and SiO_2 translates to widely different thermo-optic coefficients of TE0 and TE1.

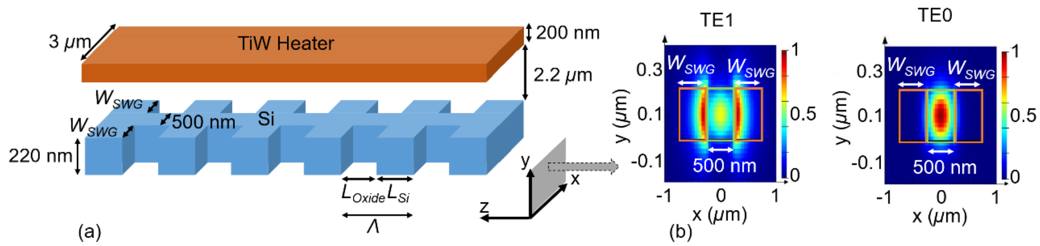

Fig. 1. (a) Schematic view of SWG-based mode-sensitive TOPS, (b) Normalized electric field distribution for TE0 and TE1 (f = 0.7 and W_{SWG} = 500 nm).

Figure 2 (a) shows the thermo-optic coefficients of TE0 and TE1 as a function of the duty ratio f for W_{SWG} = 250 nm (Fig. 1(a)). By decreasing f, one can incorporate more SiO_2 in the SWG structure leading to larger difference between the thermo-optic coefficients of the guided modes. For f=0.4, we find a thermo-optic coefficient of TE0 that is 2.2 times larger than that of TE1 (1.94 for TE0 and 0.88 for TE1.) Further decreasing f leads to weak confinement of TE1 increasing its insertion loss. This design is more focused on providing a mode-sensitive TOPS to be used in MTMOPs, where TE1 is used for monitoring applications. Therefore, the insertion loss of TE1 is relatively less of importance than in other MDM systems. Figure 2 (b) shows the thermo-optic coefficient of TE0 and TE1 versus the SWG width (W_{SWG}) for f= 0.7. By increasing the SWG width, TE1 is more confined in the SWG region with smaller electric field propagating in the silicon core region. This leads to increased differential in the thermo-optic coefficient of TE0 and TE1. However, the TOPS TiW heater width required also increases with the W_{SWG} leading to less energy efficiency.

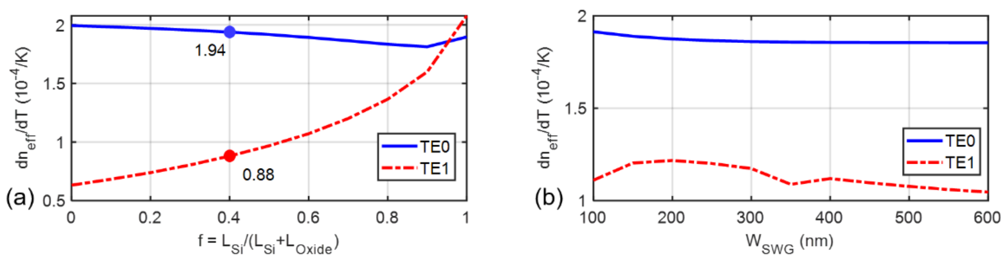

Fig. 2. (a) Thermo-optic coefficient versus duty ratio for a mode sensitive TOPS with W_{SWG} = 500 nm. (b) Thermo-optic coefficient versus W_{SWG} for f = 0.7.

Knowing f we select L_{Si} and L_{Oxide} considering the two upper and lower limits. Indeed, L_{Si} and L_{Oxide} cannot be smaller than the minimum feature size of the technology. The maximum length of L_{Si} and L_{Oxide} is set by the Bragg reflection condition ($\Lambda < \lambda_{min}/2n_{eff}$). To ensure smooth transition between the conventional waveguides and the SWG structure in the TOPS, we use adiabatic tapers with an optimized length of 20 μm [6]. Using this taper, the transition loss of TE1 from the conventional waveguide to the TOPS is less than 0.05 dB. We consider a variety of structures with f=0.4 to 0.7, Λ=220 nm to 240 nm, and W_{SWG}=200 nm to 500 nm. We will experimentally validate the fabricated TOPS and will report the results in future publications. Finally, we note that the presented design is the first step towards realizing mode-sensitive TOPS through conventional design. Larger difference between the thermo-optic coefficients with a smaller footprint would also be achievable using inverse-design methods [7].

III. Conclusion

In this work, we presented a mode sensitive TOPS design based on SWG structures. The design offers 2.2 times different thermo-optic coefficient for the first two transverse electric (TE) modes.

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