Experimentally Validated Simulation of a Mode-Sensitive Thermo-Optic Phase-Shifter

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Abstract *Mode-sensitive direct phase manipulation of two transverse-electric modes is demonstrated using two simulation approaches and verified by experimental measurement results. This design is enabled by subwavelength grating structures and serves applications such as mode switching, and a key building block in multi-mode optical processors.*

Introduction

Integrated silicon photonics fabrication exploits the affordable standard silicon-on-insulator (SOI) platform. Underdevelopment of multi-transverse mode building blocks in the past forced the waveguide dimensions to single mode operation below the cut-off conditions of higher order modes. Numerous advantages of multi-division multiplexing (MDM) scheme, such as improving the optical link budget in a power efficient manner, has driven remarkable research efforts in this domain.

Conventional on-chip MDM architectures mostly rely on firstly encoding different modes to their fundamental mode, secondly conducting the desired process by using single-mode components, and finally converting them back into their primary mode profile [1]. This approach depends on a bulky (de)multiplexing photonic circuitry that inevitably deteriorates performance compared to the scheme that can directly manipulate modes [2, 3]. However, state-of-the-art efforts mostly explored application-specific components, which lack versatility. In contrast, a versatile MDM building block that can realize a direct relative phase adjustment of higher order modes is the cornerstone of any MDM processing and switching task. We recently proposed a mode-sensitive thermo-optic phase shifter (MSTOPS) design enabled by subwavelength grating structures (SWG) as a method to engineer the thermo-optic coefficient of two fundamental transverse-electric modes (TE0 and TE1) [4]. The proposed MSTOPS, shown as δ in Fig. 1(a), is incorporated in one arm of a multi-mode 2×2 MZI building block as a test structure. Incorporating a mode-insensitive phase shifter in another arm of the MZI (φ) provides an additional degree of freedom to manipulate the relative phase shift of each mode independently resulting in a more versatile device such as a mode switch. This design can serve numerous MDM applications such as mode switching [5], multimode quantum optical processors [6], and programmable conventional integrated MZI-based optical processors [7].

In this work, we review two numerical simulation approaches to calculate the mode-sensitivity of the proposed MSTOPS. This includes a two-dimensional (2D) approach using an effective medium for the SWG sections of the device as well as a three-dimensional (3D) method to enhance the accuracy of the simulation results. Three fabricated MSTOPS with different SWG duty ratios are experimentally measured showing a thermo-optic coefficient of 44% larger for TE0 mode compared to TE1.

Device Working Principle

A schematic representation of the MSTOPS waveguide is shown in Fig. 1 (b). The electric field intensity distribution in a parallel plane to the propagation axis is calculated for both TE0 and TE1 mode profiles using Ansys Lumerical 3D eigenmode expansion solver tool. As

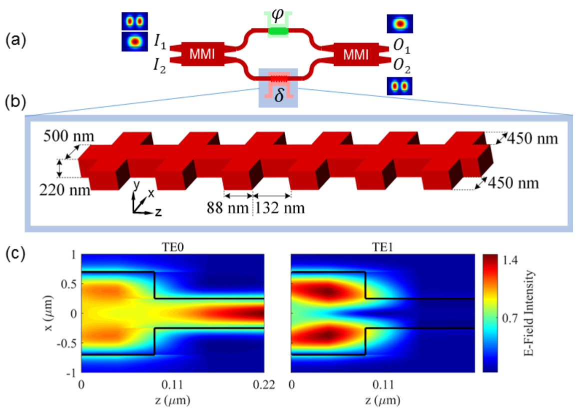

Fig. 1: (a) Schematic of the 2 × 2 MZI test structure, working as a mode switch, for experimental evaluation of the proposed MSTOPS (δ) with a mode-insensitive phase shifter (φ) as an additional degree of freedom; (b) Schematic of the SWG waveguide used in the proposed mode-sensitive phase shifter (a metal heater on top of the waveguide alters the effective refractive index); (c) Propagation behavior of both TE0, and TE1 modes in the XZ plane (i.e., top view).

demonstrated in Fig. 1 (b), TE1 energy is more concentrated in the corrugated sections, while the TE0 mode propagates through the straight waveguide core. Different thermo-optic coefficients of these regions suggest that a certain amount of an applied heat on the whole structure will produce different amounts of relative phase shifts for TE0 and TE1 mode profiles.

Simulation Methodologies

Two simulation methodologies are deployed to calculate the phase-shifter mode-sensitivity as a design figure of merit (FoM) defined as the ratio of the thermo-optic coefficient of TE0 mode over TE1 (i.e., $\zeta = (dn_{eff,TE0}/dT)/(dn_{eff,TE1}/dT)$). In both approaches, the effective refractive index of the SWG structure is calculated in two scenarios: first at room temperature, and second after applying a 100K temperature increase (assuming a uniform heat distribution over the whole structure). By considering a temperature independent thermo-optic coefficient for silicon (core) and oxide (cladding), one can realize each mode's thermo-optic coefficient as the ratio of the simulated effective index gradient to the applied temperature gradient (i.e., $dn_{eff}/dT \simeq \Delta n_{eff}/\Delta T$).

In the first simulation method, as shown in Fig. 2 (a), the corrugated sections are replaced with an effective medium of [8]:

$$n_{SWG} = \sqrt{f \cdot n_{Si}^2 + (1-f) \cdot n_{Oxide}^2} \quad (1)$$

where f is the duty cycle ratio of the SWG (i.e., silicon length over periodicity). This estimation holds for an SWG pitch of smaller than half of the incident wavelength. The resultant structure is simulated using Ansys Lumerical finite difference eigenmode solver tool as a 2D fast simulation approach considering an infinite structure along the propagation axis. This method can help with sweeping large areas of geometric parameters and roughly optimizing the SWG dimensions.

The second approach, as shown in Fig. 2 (b), involves a 3D finite difference time domain (FDTD) simulation of the nominal design without converting the corrugated sections to an effective medium. Band structure analysis is conducted to extract the mode-sensitivity FoM. It involves Fourier transform analysis of the recorded field by some randomly placed time-domain monitors in the simulation region and results in the SWG band structure as shown in Fig. 2 (c). Sweeping over different Bloch vectors leads to the angular frequency (ω) versus propagation constant (β) relation that is used for the phase velocity (i.e., $V_{ph} = \omega/\beta$) and further effective index (i.e., $n_{eff} = c/V_{ph}$) extraction.

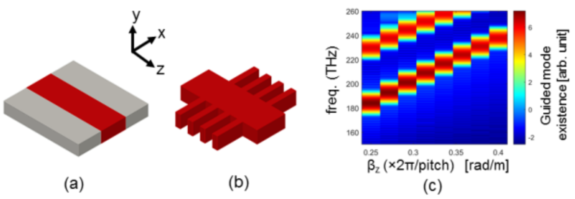

Fig. 2: (a) Modeling the SWG sections with an effective medium for an approximate 2D simulation; (b) Nominal design schematic used for 3D simulation; (c) An example of the band structure analysis results for TE1 mode at room temperature.

Experimental Evaluation

The designed MSTOPS is incorporated in one arm of a 2 × 2 multimode MZI, as schematically illustrated in Fig. 1 (a). A 4-μm wide waveguide with a metal heater on top works as a mode-insensitive phase shifter in another arm providing an extra degree of freedom to adjust the relative phase of both TE0, and TE1 modes independently. The MMI dimensions are based on a previous design [9].

The device is characterized by conducting a 2D sweep of the applied current to each phase shifter (δ and φ). The output transmission is simultaneously monitored at the bar port for both TE0, and TE1 modes. As shown in Fig. 3, the transmission behaviour of TE0 and TE1 modes are equivalent, as the applied current on φ phase shifter is changed; while the same imposed range of applied current creates a different transmission behaviour for each mode. The mode-sensitivity is experimentally extracted as the ratio of the required heating power to induce a π phase shift for both TE0 and TE1 mode profiles.

Results and Discussion

In this work, three different duty ratios of the SWG structure including f = {0.4, 0.5, 0.6} are investigated. The largest mode-sensitivity FoM of $\zeta = 1.44$ is experimentally realized for the SWG duty ratio of f = 0.4. According to Table 1, as the duty ratio increases, the amount of oxide in the corrugated area, where TE1 mode is mostly

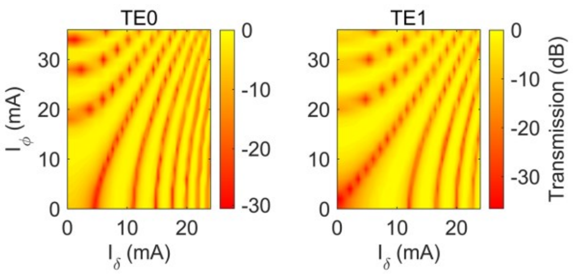

Fig. 3: 2D contour maps of the 2 × 2 MZI test structure, Fig. 1 (a), bar output transmission vs. applied current to the phase shifters for the TE0 (left), and TE1 (right) mode profiles.

Table 1: Simulation (2D, 3D) vs. experimental (Exp.) measurement results for three SWG duty ratios *f* under study.

		$\frac{dn_{eff,TE0}}{dT}$	$\frac{dn_{eff,TE1}}{dT}$	$\zeta = \frac{dn_{eff,TE0}/dT}{dn_{eff,TE1}/dT}$
***f* = 0.4**	2D	1.90	1.50	1.27
	3D	1.91	1.47	1.30
	Exp.	-	-	**1.44** ± 0.05
***f* = 0.5**	2D	1.88	1.58	1.19
	3D	1.86	1.52	1.23
	Exp.	-	-	**1.31** ± 0.03
***f* = 0.6**	2D	1.87	1.66	1.13
	3D	1.87	1.58	1.18
	Exp.	-	-	**1.20** ± 0.03

propagating, is decreased. This consequently shrinks the difference between thermo-optic coefficients of TE0 and TE1 modes. Hence, improving the FoM demands lowering the duty ratio as much as possible, where the SWG length of the silicon gets close to the minimum fabricable feature size.

The simulated thermo-optic coefficient of both simulation approaches is reported in Table 1, where the measured mode-sensitivity FoM is compared. The effective medium simulation approach (2D) provides an approximation of the thermo-optic coefficient enabled by 2D FDE simulation. In comparison with the experimental results, the 3D simulation approach can model the mode-sensitivity in a better accordance with the experimental results. The gap between the simulation and experimental results is induced from the fabrication process variation including the over/under-etching, and the rounded edges created from the lithography imperfection.

We expect that this gap would be shrank by employing a more realistic device model representation in the 3D simulation approach. An accurate topological device model could be predicted using a trained deep convolutional neural network model [10]. As an example, topological structure of a single grating is predicted and shown in Fig. 4. Comparison of the nominal design with the predicted device model (Fig.4 (b)) is shown in Fig. 4 (c), which shows existence of some over-etching effect. This can potentially contribute toward increasing the mode-sensitivity as observed in experimental results reported in Table 1. Deployment of the predicted topological model (PreFab approach), enables taking important topological factors to be taken into consideration that would not be feasible otherwise. Consequently, these involve etching uncertainties that could alter the duty

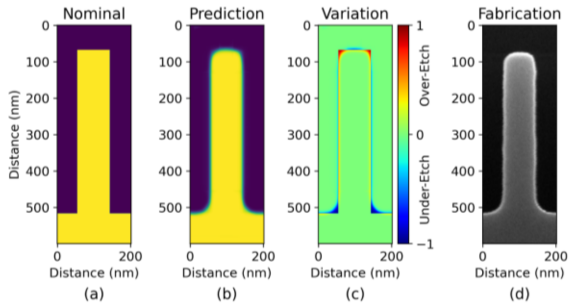

Fig. 4: Nanofabrication prediction and analysis of a single grating: (a) nominal design; (b) predicted design; (c) over/under-etching analysis by comparing the nominal vs. predicted designs; (d) SEM image of a single fabricated grating.

ratio and mode-sensitivity.

Conclusions

A mode-sensitive thermo-optic phase shifter is proposed to directly manipulate the relative phase of two transverse-electric modes (TE0 and TE1). This novel functionality is enabled by subwavelength grating (SWG) structures and serves numerous applications in mode division multiplexing (MDM) systems, including switching in optical networks, and potentially as a building block for scaling-up conventional MZI-based optical processors. A mode-sensitivity of 1.44 is experimentally demonstrated in well accordance with the deployed 3D simulation approach. The observed small gap between simulation and experimental results is justified by observation of over-etching. Deploying a trained neural network to predict the fabrication process variation (PreFab) could enhance 3D simulation results accuracy. This simulation approach paves the road for attaining an improved mode-sensitivity by shrinking down the SWG duty ratio, in which the corrugated length of silicon gets close to and beyond the minimum fabricable feature size without compromising the device performance.

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