Thermal tuners on Silicon Nitride: performance and crosstalk analysis

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Thermo-optic tuners on a silicon nitride platform are thoroughly studied. The heater width and length are parametrized in order to characterize the optimal power consumption required for a π-phase shift. The trade-off between tuning power and crosstalk is also studied together with the effect of thermal isolation produced by selective area trenching.

Introduction

The function integration density in photonic integrated circuits (PICs) grows at a similar pace to electronics [1]. With more and more components on a photonic chip, where a non-negligible number are equipped with electronic pads for biasing and tuning, proximity issues in the electrical and optical domain are being subject of growing interest [2]. One of the most resourceful tuning mechanisms for most of the PIC building blocks is the thermal tuner, which is enabled by the temperature dependence of the guiding properties in optical waveguides. Two topics are relevant with regards to these tuners. Firstly, since many reconfigurable devices may need a huge amount of thermo-optics, the tuner efficiency determines the overall chip power consumption. The electrical DC power needed to shift the phase by π is a good figure to quantify and compare the efficiency of a thermal tuner. Secondly, albeit from a purely photonic perspective the possibility of reducing the chip area or increasing the number of components, the complexity and the overall performance of the chip, heat diffusion poses limitations in terms of how close other photonic components may be placed, to prevent thermal cross-talk.

Therefore, there is a trade-off which requires a study of thermal crosstalk and its significance. Some research has been made in silicon on insulator (SOI) with a 3,00% thermal crosstalk at 15 µm, [3], 1.6% at 250 µm, [4], 3% at 60-180 µm, [5], and a 25% at 0.2-0.5 µm, [6]. Also, thermal crosstalk has been quantified in Indium Phosphide, were active components like SOAs act as heat sources, [7].

With regards to silicon nitride the common design rule is to place the components more than 100 µm from the heat source, but a systematic theoretical and experimental analysis has not been reported in the literature. The materials of the waveguide and the cross-section size and distribution lead to different results when comparing crosstalk in the different platforms and foundries.

Furthermore, a common technique to prevent heat conduction in PICs is the use of trenches as a way to reduce the thermal-crosstalk, and it has been proposed for all the platforms, [8, 9].

In this paper, we present a thermal-crosstalk analysis on a novel silicon nitride platform. We have design 23 test structures that consist of Mach-Zehnder Interferometers (MZI) based on silicon nitride deeply etched waveguides, in order to measure the electrical power required for a π-phase shift and the thermal-crosstalk associated to that temperature. It is also proposed and studied the effect of thermal isolation produced by selective area trenching for improving the efficiency of the thermo-optics devices and reducing the thermal-crosstalk distance.

Thermo-optics efficiency

A thermo-optic tuner is a thin film electrical conductor that produces heat by Joule effect by the passage of an electric current through it. The refractive indices variation of the cladding and the core with temperature for a waveguide lying beneath, or in the vicinity of, the thermal tuner, produces a change in the guided mode effective index. Tuning through thermo-optic effects has the lowest associated optical loss, provided the metal conductor is sufficiently far apart from the optical mode, but power efficiency and speed are the main drawbacks. To overcome these limitations, alternative tuning methods such as free-carrier electro-optic effects are also possible, but also have higher optical losses.

The phase shift when propagating depends on the effective index through:

$$\Delta\Phi = \beta L = \frac{2\pi n_{eff}(\lambda, T)}{\lambda} L \tag{1}$$

The thermal properties of the material define the heat distribution and the conduction speed. In general, silicon oxide and silicon nitride have low thermal conductivity *1.4* and $30.5 W/(m \cdot K)$ respectively and a low thermo-optic coefficient, $1.5 \cdot 10^{-5}$ and $4.5 \cdot 10^{-5}\ 1/K$, so temperature change is slow and high power is required to change the temperature at the waveguide core. This means these waveguides are less sensitive to environmental temperature changes and its thermal-crosstalk security distance will be shorter. The former is especially useful due to recent studies indicate that temperature control represents around 50% of the total power consumption budget [10], so such a small thermal sensitivity could offer a reduction on the power related to temperature control of the chip.
On the other side, materials like Indium Phosphide have a thermal conductivity of $68 W/(m \cdot K)$, having a larger thermal-crosstalk distance and being more sensitive to temperatures changes.

To test the thermal tuners, they are embedded as part of a Mach Zehnder Interferometer (MZI) test structure. A total of 23 are designed, with parametric variations in a Silicon Nitride technology [11] multi-project wafer cell of 5.5x5.5 mm^2. The MZIs have been designed to have an FSR of 2 nm. The thermal tuner is placed on top of the MZI upper arm waveguide. For each MZI test structure, the thermal tuner width and length are varied. The heater is composed of a *50 nm* layer of chromium and a *150 nm* layer of gold at the top [11]. The waveguide cross-section with heater, and the thermo-optic MZI test structure are shown in Fig. 1.

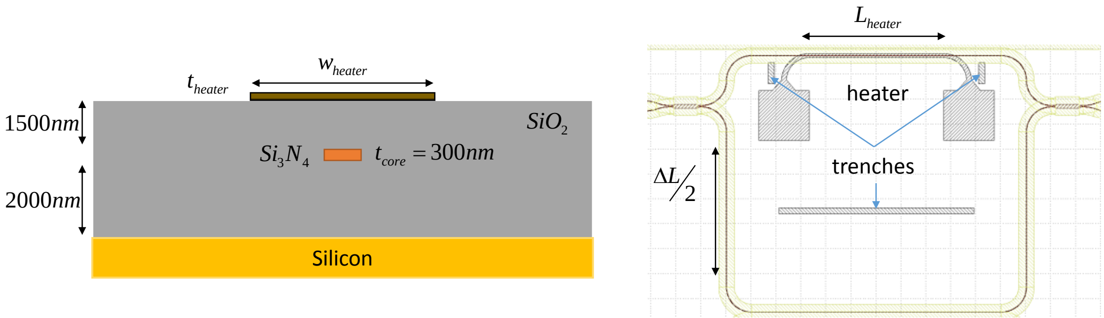

Fig 1:Cross-section of the CNM waveguide (left), topview of the MZI used as a test structure

The phase shift induced by a temperature change in the MZI is described by:

$$\Delta\Phi = \beta L = \frac{2\pi}{\lambda} \cdot \frac{\partial n_{eff}}{\partial T} \cdot \Delta T \cdot L_{heater} \qquad (2)$$

where $\frac{\partial n_{eff}}{\partial T}$ is the thermo-optic coefficient of the waveguide, ΔT is the change in temperature and $L_{heater} = L_h + L_{eff}$ is the heater length composed of the length of the film over the core with the addition of the distance where the heat propagates as can be seen in Fig. 2 (right).

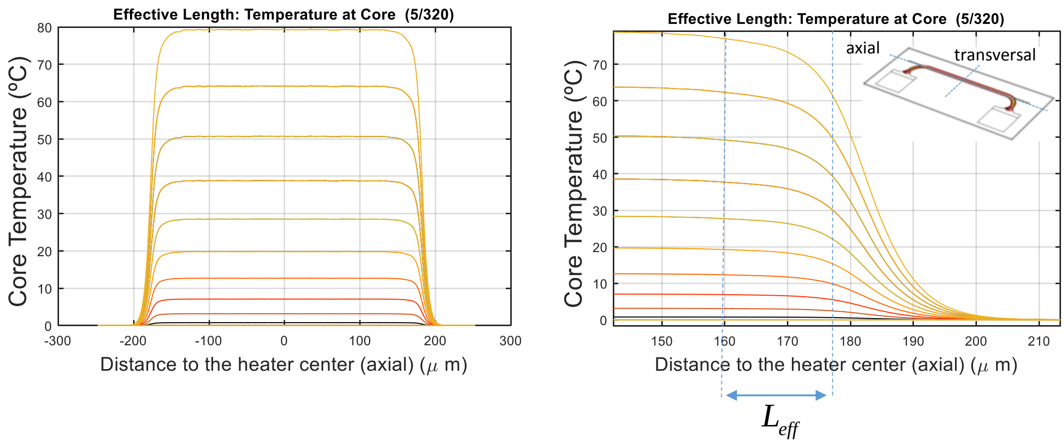

Fig 2: Temperature distribution at core level in the axial axis (left and right), effective length explanation (right)

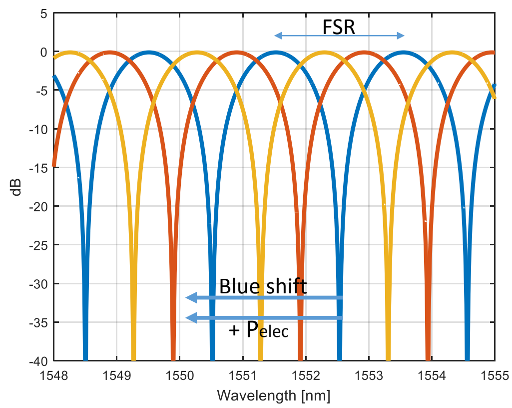

Fig 3: MZI tunable response for different heater power supply levels

For heater length ranging from 120 to 320 µm and heater width from 5 to 8 µm. P_π has values from 195 mW to 380 mW. Efficiency is maximum for long and narrow heaters. Since the FSR is 2 nm, the most efficient tuner in our analysis performs at 195 mW/nm (blue shift).

This value may be improved with the use of trenches, which may confine heat in the area surrounding the waveguide, as discussed in the following section.

Thermal isolation produced by selective area trenching

Trenches have been proposed as a way to avoid conduction and prevent from thermal-crosstalk between guides. Nevertheless its main application in this waveguides is to manage the heat distribution and concentrating it through the waveguide core. Simulations show a 20 % reduction of the P_{π}, and a reduction from 10.9 µm to 8 µm for less than 3% cross-talk, for a heater length and width of 320 µm and 5 µm respectively.

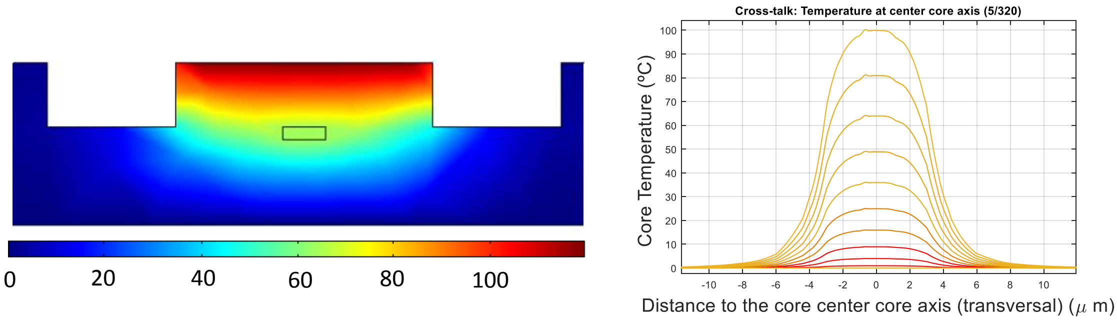

Fig 4: Cross section and heat distribution and transversal temperature at core level

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