Thermal Crosstalk reduction in InP based Photonic Integrated Circuits

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Abstract: *In this paper we numerically investigate the thermal crosstalk reduction that can be obtained by etching deep trenches in Indium Phosphide based photonic integrated circuits. We show how deep trenches between adjacent components modify the heat transfer path. The current injected in active components and the geometry of the trenches are the parameters considered in our analysis. We demonstrate how the geometry of the trenches play a role in the reduction of the thermal crosstalk. The numerical results show a reduction of the distance between components up to 50%.*

Introduction

Since the introduction of the Arrayed Waveguide Grating (AWG) in 1988 [1] the complexity of Indium Phosphide (InP) based Photonic Integrated Circuits (PIC) has increased exponentially from a few to a few hundreds components. Significant progress in the development of PICs were reported with the introduction of WDM receivers [2] and transmitters [3]. The most severe limitations to further chip complexity development are: *i*) the unavoidable losses in passive components that restrict the total number of components that can be cascaded, *ii*) in active PICs the number of Semiconductor Optical Amplifier (SOA) is typically restricted up to a maximum of a few hundreds, because of heat sinking limitations and *iii*) the optical, electrical and thermal interaction between components, commonly identified with the term *crosstalk*. The most problematic crosstalk contributions in PICs are: the radiofrequency crosstalk, mostly related to the inductive and capacitive coupling; the optical crosstalk, related to unwanted phenomena as scattering, coupling and reflection of light; and the thermal crosstalk, due to the heat transfer from active components, i.e. SOA to passive components i.e. waveguides, phase modulators, AWG.

This paper focuses on the thermal crosstalk between components. Here we investigate how the thermal crosstalk affects the performance of a generic PIC and moreover we investigate the thermal crosstalk reduction that can be obtained by defining rectangular-shaped deep trenches between active and passive components.

Electro - Thermal model

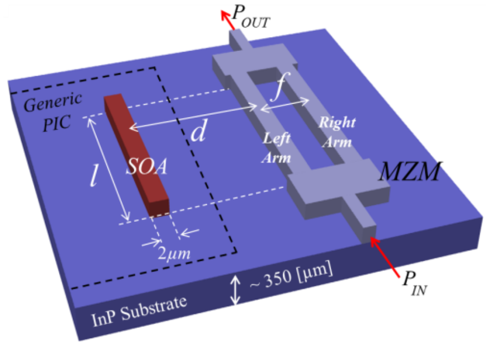
By using a 3D finite elements method, we model the electro–thermal interaction in active components and the heat transfer from them to the rest of the PIC. Our model works as follows: *a*) A current *I* is injected in the active components, such as SOAs, and the Joule’s heating is calculated, *b*) The heat transfer from the SOAs to the rest of the PIC is evaluated by solving the heat transfer equation, *c*) The local temperature in every interesting point of the PIC is evaluated. We simplify the heat transfer equation by considering the steady state regime, so that the equation governing the pure conductive heat transfer in a solid become:

$$C_p \rho \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q \qquad (1)$$

where k [W/(m·K)] is the thermal conductivity, ρ [kg/m^3] is the material density, C_p [J/(kg·K)] is the specific heat capacity at constant pressure, T [ºK] is the absolute temperature. Q [W/m^3] contains the heat sources and it is related to the Joule's effect.

Thermal crosstalk simulations

In Figure 1 (left), we consider a simple photonic circuit based on one SOA and one Mach-Zehnder (MZ) modulator. The SOA is part of a more complex section of the PIC but it is not related to the MZ.



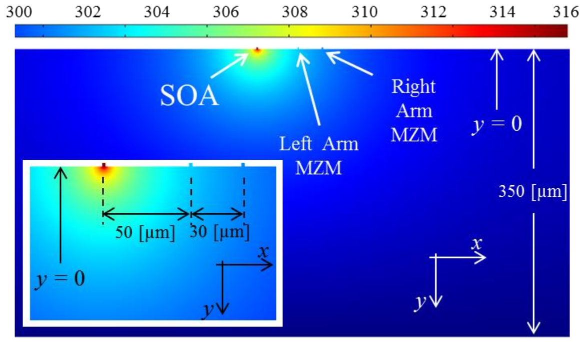


Figure 1: (left) Photonic integrated circuit considered in our model and (right) Temperature distribution when a current density of 10000 [A/cm^2] is injected in the SOA (200 mA for a SOA length of 1 mm).

To reduce the number of geometrical variables we consider the same length, l, for the SOA and for MZ arms. Moreover we consider the distance between the arms of the modulator fixed: f = 30 μm. The thickness of the InP substrate is t = 350 μm. d is a variable in our analysis. The temperature of 300 [ºK] is imposed at the bottom side of the chip by a copper heat sink (not shown in Figures 1) whose thermal conductivity is high enough to ensure a fixed temperature. Figure 2 (left) shows the SOA peak temperature, versus the injected current density. The quadratic behavior is due to the Joule's effect. Figure 2 (Right) shows the temperature distribution along the x-coordinate (with y = 0) as a function of the current density injected in the SOA. The left and right arms of the MZ are, respectively, at distance d and d+f, from the SOA and then, from Figure 2 (Right), the arms of the MZ are at different temperature. The mismatch in temperature, and then the mismatch in the refractive index, leads to a variation of the output optical power, with respect to the ground state (i.e. J =0). The optical output power Pout, can be expressed as:

$$P_{out} = E_0 \cdot E_0^* \quad \text{where} \quad E_0 = \frac{E_{in}}{2}\left[e^{-j\frac{2\pi}{\lambda}n_L L} + e^{+j\frac{2\pi}{\lambda}n_R L} \right] \cdot e^{-\alpha l} \qquad (2)$$

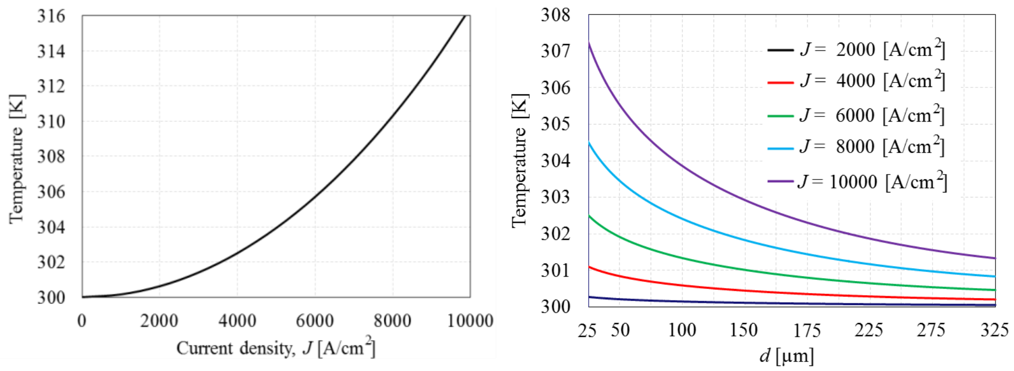


Figure 2: (Left) Peak temperature in a single SOA *vs* injected current density and (Right) Temperature distribution along the *x*-coordinate of the InP chip, with $y = 0$.

For the arms of the MZ we assume as optical loss α = 2 [dB/cm] and we neglect its dependence with the temperature, because it does not change significantly for small temperature variations. E_{in} in equation (3) is the unitary field considered as MZ optical input, while n_L and n_R are, respectively, the effective refractive index for the left and right arm of the MZ modulator. Both n_L and n_R depend on the temperature: $n_{R(L)}=n_0+\eta\Delta T$. n_0=3.25 is the effective refractive index considered for each arm of the MZ at T=300 [ºK], while $\Delta T_{L(R)}$ is the temperature variation in the arm. The coefficient $\eta=2.5\cdot10^{-4}$ [1/ºK] is the thermo-optical coefficient considered for InP.

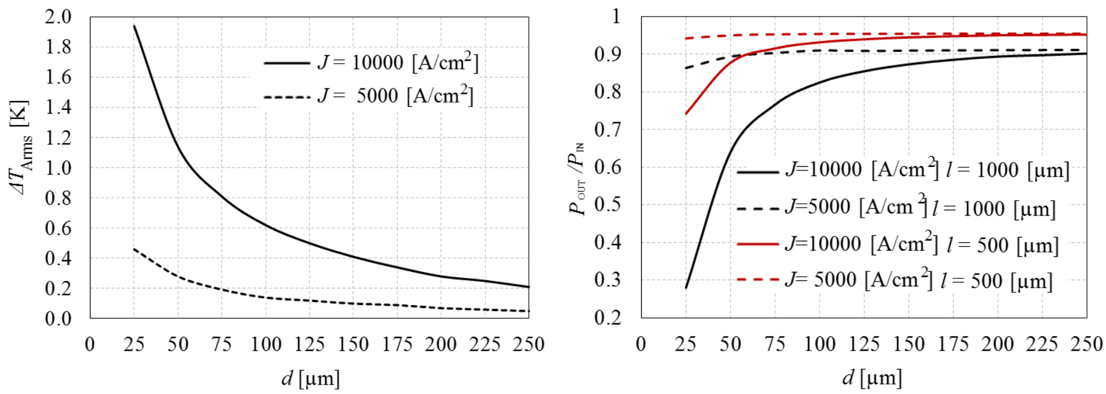


Figure 3: (Left) temperature difference between the left and right arm of the MZ and (Right) Pout *vs* position of the MZ for two length and two values of injected current.

Figure 3 (left) reports the difference in temperature between the two arms of the modulator as a funcion of the distance between modulator and SOA for two values of current density injected in the SOA. Figure 3 (Right) shows the effect of the thermal crosstalk to the optical output power for two different MZ lenghts and for two values of injected current. For high values of *d*, P_{out} is only limited by the waveguide losses.
Up to *l*=1 mm, we consider the SOA and the MZ "isolated", when P_{out} > 0.9P_{in} for a current density value up to 10000 A/cm^2. For instance, the minimum values of *d* (d_{MIN}) to avoid the crosstalk effects for J = 10000 [A/cm^2] and l = 1000 µm, is d_{MIN} ~ 240 µm.

Trench effects

The trenches are intended as deep apertures between components with the purpose to modify the heat transfer path. They do not modify the optical properties of the waveguides because they are far from the guiding structures. We consider the trench positioned in the middle between the SOA and the MZ. To evaluate the performances of the trenches we consider the case of J = 10000 [A/cm^2] for a length l = 1000 µm. In this case d_{MIN} is 240 µm if no trenches are considered between the SOA and MZ.

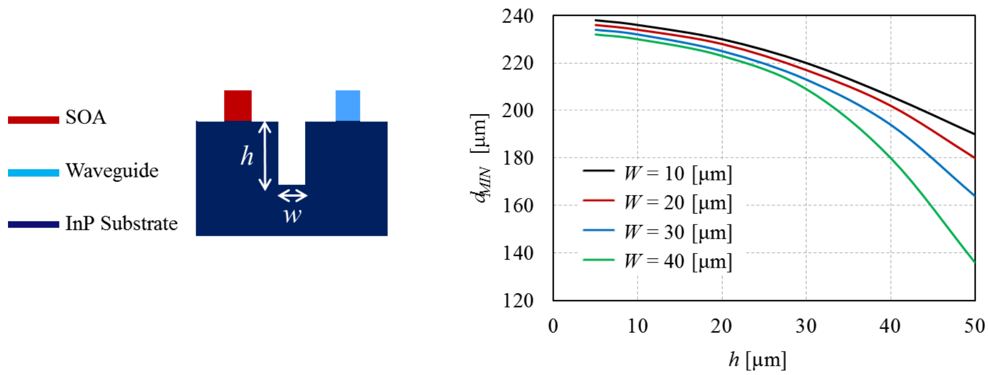


Figure 4: (left) Trench geometrical definition and (right) Reduction of the minimum distance between components due to the trenches.

Figure 4 (Right) shows the effect of the trench in relation to its geometry. Both parameters w and h play a role in the modification of the heat transfer path. The depth of the trenches is not critical for the mechanical integrity of the InP wafer since it is, in the most severe case reported in our simulation, less than 20% of the total thickness of the wafer. Moreover the trenches are localized around the active components and they do not cover the whole chip. From our simulation the trench with w = 40 µm and h = 50 µm allows the reduction of the distance between SOA and MZ up to 135 µm: more than 40% if compared with the case without trenches, where d_{MIN} is 240 µm.

Conclusions

We have developed a model to investigate the thermal crosstalk effect in photonic integrated circuits including both active and passive components. The model is applied to investigate the thermal crosstalk reduction that can be obtained by etching deep trenches between active and passive components. We demonstrate how the geometries of the trenches play a role in the reduction of the thermal crosstalk. The numerical results show that the distance between components can be reduced up to about 50%.

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