Efficient thermal cross-talk effect cancelation in photonic integrated circuits

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Abstract: A novel technique, named Thermal Eigenmode Decomposition, able to cancel the effects of thermal cross-talk in arbitrary photonic circuits with heaters is presented. The mapping of thermal cross-talk is obtained only with electrical measurements.

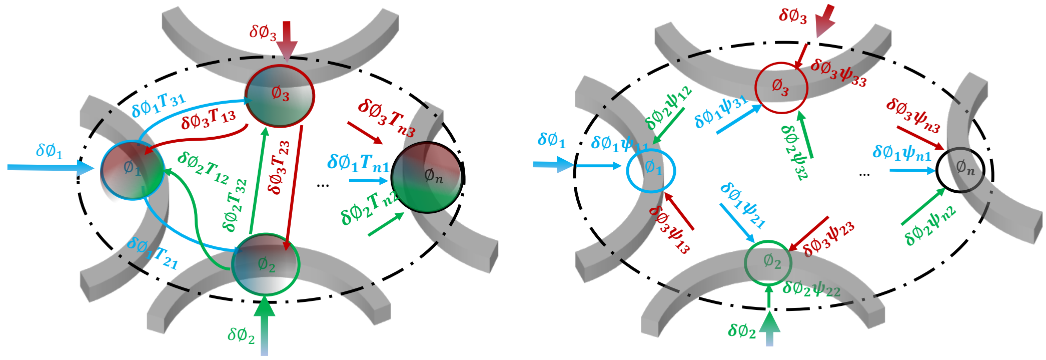
OCIS codes: (230.3120) Integrated optics devices; (230.5750) Resonators; (230.7408) Wavelength filtering devices

1. Introduction

Photonic integrated circuits (PICs) are extremely sensitive to any kind of phase perturbation in the optical waveguides, which can be originated by tolerances of the fabrication process as well as by temperature changes induced by thermal gradients across the photonic chip. To compensate against phase errors, actuators capable of controlling actively the phase in optical waveguides are required.

Thermal actuators are a well-established approach [1] however, they can induce mutual thermal cross-talk between neighbor actuated waveguides and thus can impair the efficiency of control procedures employed for PIC tuning and stabilization. Conventional solutions to mitigate thermal cross-talk include thermal isolation trenches allow the localization of the heat around the actuated waveguide and can also improve the heater efficiency [2].

In this contribution we present a novel method, named *Thermal Eigenmode Decomposition* (TED), which can be used to cancel out the effects of thermal cross-talk in arbitrary PICs where thermal cross-talk is indeed physically present. Through experimental trials we demonstrate more efficient convergence rate by TED based tuning compared to individual modification of actuators separately. Our results show that TED provides significant performance improvement with respect to individual tuning of thermal actuators even when partial knowledge of the **T** matrix is available, for instance from empirical models, numerical thermal simulations or indirect measurements.



(a) (b)

Fig. 1: **(a)** Schematic representation of a PIC integrating *N* phase actuators in presence of phase coupling induced by thermal cross-talk. **(b)** TED concept: the effects of thermal cross-talk are cancelled by simultaneously driving all the coupled actuators according to the eigenmodes of the thermally coupled system.

2. Thermal eigenmode decomposition (TED)

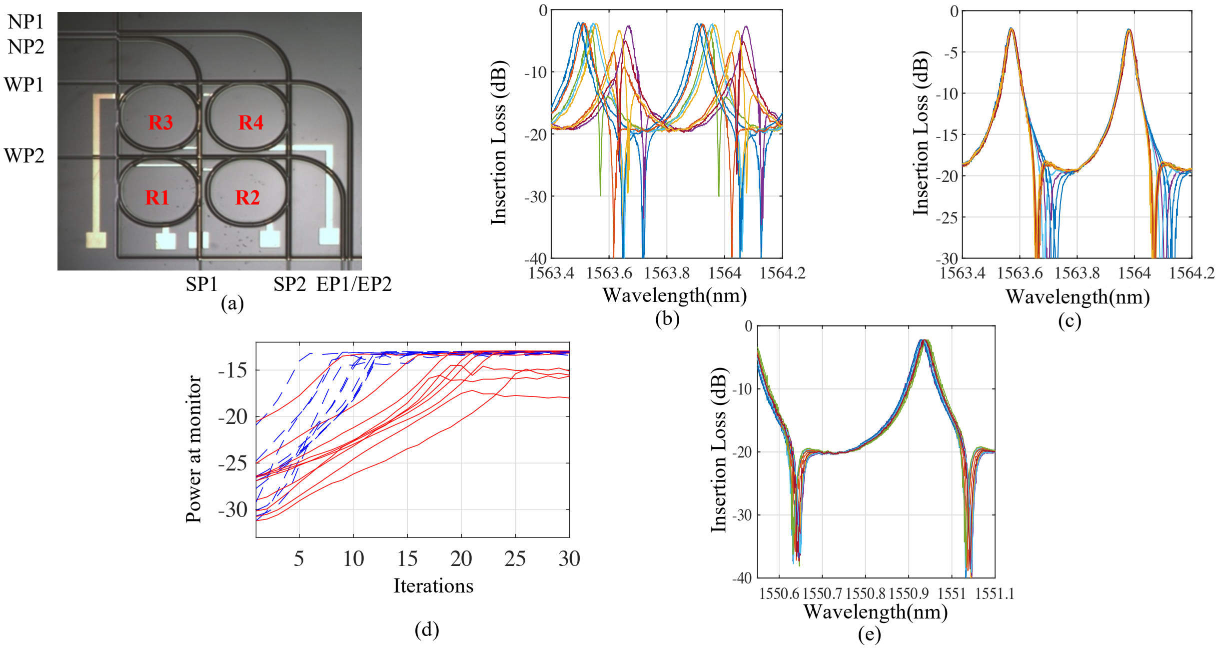
To illustrate the concept of the TED method, let us consider the schematic of Fig. 1(a) showing an arbitrary PIC consisting of *N* optical waveguides with a thermal actuator integrated in each of them. The status of the circuit is identified by the phase vector $\mathbf{\Phi} = [\Phi_1 \; ... \; \Phi_N]^{\mathrm{T}}$, where Φ_n is the current phase in the *n*-th waveguide. When an electrical power is applied to the *n*-th actuator, it is expected to introduce a desired phase change $\delta\Phi_n$ to the *n*-th waveguide where the actuator is integrated, with no effects on the surrounding waveguides. However, due to thermal cross-talk, some phase perturbations are also introduced in the other waveguides. Considering Fig. 1(a) the actual phase shifts $\delta\widetilde{\mathbf{\Phi}} = [\delta\widetilde{\Phi}_1 \; ... \; \delta\widetilde{\Phi}_N]^{\mathrm{T}}$ induced in each waveguide is given by $\delta\widetilde{\mathbf{\Phi}} = \mathbf{T}\delta\mathbf{\Phi}$ where $\delta\mathbf{\Phi} = [\delta\Phi_1 \; ... \; \delta\Phi_N]^{\mathrm{T}}$ is the desired phase shift and **T** is the phase coupling matrix taking into account all the self (diagonal) and cross (off-diagonal) phase shift contributions. The phase coupling coefficient T_{nm} between the n-th actuator and the m-th waveguide depends on the PIC topology, photonic platform and not on the status of the circuit.

The proposed TED [3] method provides a strategy to cancel out the unwanted effects of thermal cross-talk on the actual phase shift applied to the optical waveguides. Mathematically, the concept is a coordinate transformation, mapping the phase variables $\boldsymbol{\Phi}$, which are (thermally) coupled by the $\mathbf{T}$ matrix, into a suitable set of uncoupled phase variables $\boldsymbol{\Psi} = [\delta\Psi_1 \ \ldots \ \delta\Psi_N\,]^{\mathrm{T}}$, for which the phase coupled matrix $\mathbf{T}$ becomes diagonal. Assuming $\mathbf{T}$ to be diagonalizable we can write $\delta\widetilde{\boldsymbol{\Phi}} = \mathbf{P}\mathbf{T}_{\mathrm{D}}\mathbf{P}^{-1}\delta\boldsymbol{\Phi}$ where $\mathbf{P}$ is a matrix whose columns are linearly independent eigen-vectors of $\mathbf{T}$, $\mathbf{T}_{\mathrm{D}}$ is the diagonal matrix containing the corresponding eigen-values, and $\mathbf{P}^{-1}$ is the inverse matrix of $\mathbf{P}$. Multiplying both sides by $\mathbf{P}^{-1}$ we obtain $\delta\widetilde{\boldsymbol{\Psi}} = \mathbf{T}_{\mathrm{D}}\delta\boldsymbol{\Psi}$ where $\delta\boldsymbol{\Psi} = \mathbf{P}^{-1}\delta\boldsymbol{\Phi}$ is the phase shift imparted to the transformed phase variables $\boldsymbol{\Psi}$. Since $\mathbf{T}_{\mathrm{D}}$ is diagonal, any change in each element of vector $\boldsymbol{\Psi}$ does not affect the other elements. In other words, the elements of $\boldsymbol{\Psi}_n = \mathbf{P}_n^{-1}\boldsymbol{\Phi}$, where $\mathbf{P}_n^{-1}$ is the n-th row of the $\mathbf{P}^{-1}$ matrix, identify orthogonal directions in a transformed phase space, enabling to apply uncoupled, and hence well controllable, phase modifications to the system. Once phase mapping through TED is performed, any tuning and locking algorithm can be implemented by using the transformed coordinates $\boldsymbol{\Psi}$ as the phase state variables of the system.

3. Experimental results

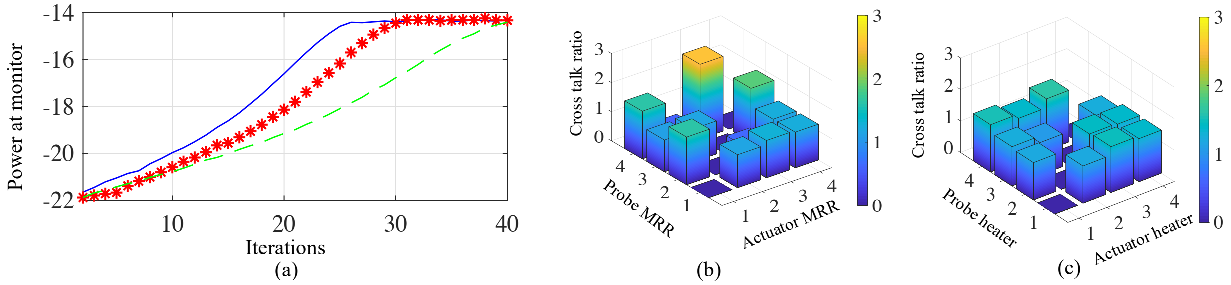
The effectiveness of the TED-based method has been experimentally validated on a 2x2 cross-bar interconnect of microring resonators (MRRs). Fig. 2(a) shows a top view microphotograph of the device, which was fabricated in a high-index-contrast silicon oxynitride (SiON) photonic platform [4]. The SiON channel waveguide (2.2 µm x 2.2 µm) has a refractive index contrast of 4.4% and the MRR resonators have a free spectral range of 50GHz). The round trip phase of each MRR of the filter can be individually controlled by means of metallic heater deposited on top of the waveguide uppercladding. In the reported experiments, we employed 5 Gbit/s OOK modulated signals at the input ports of the PIC, because this data-rate well matches the 7 GHz passband of the MRR filters, but results can be extended to signals and MRRs with higher bandwidth.

To test the TED method, phase perturbations were intentionally introduced in every MRR of the PIC by applying random errors in the voltages driving the heaters around their optimum tuning point. Fig. 2 (b) shows the measured transfer function (input WP2 - output SP2) when the TED tuning algorithm was targeted for maximizing the output power at the SP2, while injecting at port WP2 a 5Gbit/s signal with carrier wavelength of 1563.98 nm. Fig. 2 (c) shows that, regardless of the initial perturbation, the filter was effectively tuned to the same shape routing the channel to SP2.



(a) (b) (c) (d) (e)

Fig. 2: Experimental validation of automatic tuning based on TED method. **(a)** Top view photograph of an interconnect of 4 MRR filter fabricated in SiON technology. Measured transmission of the WP2 to SP2 of the filter **(b)** for 10 randomly perturbed configuration induced by using thermal phase shifters and **(c)** after automated tuning performed by using TED method. **(d)** Convergence rate of TED based tuning (blue-dashed curves) versus individually tuning of the MRRs (red-solid). **(e)** Measured transmission of the MRR interconnect (WP2-SP2) tuned for the routing of two channels (labeled via shallow modulation).



(a) (b) (c)

Fig. 3: (a) Convergence rate of TED-based tuning of the PIC of Fig. 2 (starting from same initial perturbed conditions) when: the off-diagonal terms of the phase coupling matrix **T** are assumed to be identical (green dashed curve) and when they are derived from electrical measurements (red asterisks) and from optical measurement (blue solid curve). (b) Optically and (c) electrically measured off-diagonal terms of the phase coupling matrix T normalized to average value.

The TED method was then compared to the individual tuning (i.e. each MRR individually controlled, with no thermal cross-talk compensation) in terms of convergence ratio and speed. Figure 2(d) shows that, starting from the same perturbed configurations of Fig. 2 (b), individual tuning may fail to converge to the target filter shape, whereas the TED-based tuning did converge for all the considered initial cases in less than 20 iterations.

The TED-method was also used to route two channels, namely $\lambda_1 = 1550.93$ and $\lambda_2 = 1551.03$, which are simultaneously injected at input port WP2, to output ports SP2 and EP1, respectively. To this aim, the two signals were labeled each via a shallow modulation tone [5] and the tuning algorithm was targeted to maximize the ratio between the amplitude of the tones at output port SP2. From Fig. 2(e) it can be appreciated that, with respect to the single channel routing of Fig. 2(c), the frequency response of the MRR router is here optimized both at the peak of the transmission curve (λ_1) and at the notch (λ_2), while in the previous experiment the position of the notch was not targeted by the tuning algorithm.

Best performance of TED method is achieved when off-diagonal (cross-talk) terms of the phase coupling matrix **T** are precisely known. However, accurate information on thermal cross-talk may be hardly available in practical cases. In Fig. 3(a) we evaluated the convergence of TED algorithm for the PIC of Fig. 2 when the off-diagonal terms of the phase coupling matrix **T** are assumed to be identical (green dashed line) and when they are inferred from optical measurements (blue curve) and from electrical measurements (red asterisks). The **T** matrix derived from optical measurements (by measuring the cross-induced shift among all the MRRs, see Fig. 3(b)) provides the fastest convergence, but it is hardly accessible in most cases, because it requires the possibility to individually measure the cross-induced phase shift between optical waveguides. In contrast, good estimation of **T** matrix is easily achievable electrically (see Fig. 3(c)), by measuring the temperature-induced change of the resistance of probe resistors integrated on chip. Even though the **T** matrix measured electrically differs from the one measured optically, convergence rates in Fig. 3(a) reports performance improvement over theoretical phase coupling matrix with identical off-diagonal terms.

4. Conclusion

In this work we introduced a novel technique, named Thermal Eigenmode Decomposition, capable of cancelling the effects of thermal cross-talk in arbitrary photonic circuits where heathers are presented. We show with electrical measurements we can obtain a good estimation of thermal cross-talk. This technique is a general concept and can be adopted for any tuning and locking schemes implemented in arbitrary dielectric and semiconductor platforms.

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References

[1] N. C. Harris, Y. Ma, J. Mower, T. Baehr-Jones, D. Englund, M. Hochberg and C. Galland, "Efficient, compact and low loss thermo-optic phase shifter in silicon," *Optics Express,* vol. 22, no. 9, pp. 10487-10493, 2014.

[2] D. Pérez, I. Gasulla, L. Crudgington, D. J. Thomson, A. Z. Khokhar, K. Li, W. Cao, G. Z. Mashanovich and J. Capmany, "Multipurpose silicon photonics signal processor core," *Nature Communications,* vol. 8, p. 636, 2017.

[3] M. Milanizadeh, D. Aguiar, A. Melloni and F. Morichetti, "Cancelling thermal cross-talk effects in photonic integrated circuits," *Journal of Lightwave Technology,* p. Submitted.

[4] A. Melloni, F. Morichetti, G. Cusmai, R. Costa, A. Breda, C. Canavesi, and M. Martinelli, "Progress in large integration scale circuits in SiON technology," in *Transparent Optical Networks*, Rome. Italy, 2007.

[5] S. Grillanda, F. Morichetti, N. Peserico, P. Ciccarella, A. Annoni, M. Carminati and A. Melloni, "Non-Invasive Monitoring of Mode-Division Multiplexed Channels on a Silicon Photonic Chip," *Journal of Lightwave Technology,* vol. 33, no. 6, pp. 1197-1201, 2015.