Automatic configuration and wavelength locking of coupled micro ring resonators in presence of thermal cross-talk.

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ABSTRACT

Thermal cross-talk can impair the efficiency of tuning algorithms employed for the control, calibration and reconfiguration of photonic integrated circuits (PICs). For example, in coupled microring resonator (MRRs) architectures, thermal crosstalk is responsible for an unwanted coupling among the round-trip phases of the resonators, thus affecting their resonance frequencies. Here we propose a novel approach, named Transform Coordinate method (TCM), enabling thermal cross-talk cancellation in PICs. In the TCM, instead of controlling the phase shift of each photonic element individually, the eigensolutions of the thermally coupled system are calculated and employed as control variables. The effectiveness of the TCM is demonstrated by implementing a feedback control system providing automatic resonance tuning of 3rd order coupled MRR filters. Numerical simulations, confirmed by experimental results achieved on a high-index-contrast silicon oxynitride (SiON) platform, demonstrate that the TCM enables a tuning process that is faster, more accurate and more robust with respect to conventional methods based on individual tuning of each MRR. Further, the TCM can be used as a wavelength locking algorithm to maintain the tuned condition in the presence of temperature drift as well as random fluctuations of the wavelength and of the power of the input signal. Finally, the TCM can be applied to generic PIC architectures based on arbitrary combinations of MRRs and other integrated interferometric devices.
Keywords: Microring resonators, Feedback control, integrated optics, thermal cross-talk cancelation,

1. INTRODUCTION

To compensate fabrication tolerances or for reconfiguration purposes, actuators capable to control actively the phase shift in optical waveguides are required. To this aim, thermal actuators, locally modifying the refractive index of the waveguide by thermo-optic effect, are a well-established approach. However, thermal crosstalk effects between actuators controlling neighbour elements of the same photonic integrated circuit (PICs) or among different PICs integrated onto the same chip may cause mutual unwanted phase perturbations and impair control procedures. In these conditions, conventional methods based on the control of the phase shift of each photonic element individually, are not efficient, as they may require a large number of iterations, or they can even fail to converge.
In this contribution we present a novel method, named *Transformed Coordinate method* (TCM), that can circumvent thermal cross talk effect and allows to automatically configure and stabilize PICs with no penalties introduced by thermal coupling between different actuators. In the TCM, instead of controlling the phase shift of each photonic element individually, the eigensolutions of the thermally coupled system are calculated and employed as control variables. The effectiveness of the proposed method is demonstrated by numerical simulations and experiments carried out on PIC architectures based on coupled micro ring resonator (MRRs). We show that the TCM enables a faster convergence of the tuning process and that it can be used as a wavelength locking strategy to preserve the tuned condition of the filter in the presence of temperature drift and random fluctuations of the wavelength and of the power of the input signal.

2. TRANSFORMED COORDINATE METHOD (TCM)

To illustrate the basic concept of the TCM approach, let us consider an arbitrary PIC architecture including N thermal actuators for control and reconfiguration. When an electrical power is applied to the i_{th} actuator, it is expected to introduce a desired phase change $\delta\Phi_i$ to the i_{th} waveguide where the actuator is integrated, with no effects on the surrounding waveguides. However, due to thermal crosstalk, some phase perturbations are also introduced in the other waveguides too. The actual phase shift $\Delta\Phi_i$ induced in each waveguide is thus given by $\underline{\boldsymbol{\Delta\Phi}} = \boldsymbol{T}\underline{\boldsymbol{\delta\Phi}}$ where $\boldsymbol{T}$ is the phase coupling matrix relating the phase shift in each waveguide to the phase shift in each actuator. Each phase coupling coefficient T_{nm} between the *m-th* actuator and the *n-th* waveguide strongly depends on the PIC topology. In the absence of thermal crosstalk, the **T** matrix is diagonal since all off-diagonal terms T_{nm} (with $m \neq n$) vanish. Individual modification of phases $\delta\Phi_i$ is not an effective method for controlling the system, since at every iteration there is the need for cancelling the thermal crosstalk introduced at the previous step. This leads to the increase of required iterations to get convergence or may even result to divergence.

The aim of the TCM is to cancel out the phase coupling in each iteration. Mathematically, this means to handle a diagonal phase coupling matrix. Considering T to be diagonalizable we can introduce $\boldsymbol{D}$ as diagonalized matrix of T as $\Delta\underline{\boldsymbol{\Phi}} = \boldsymbol{PDP}^{-1}\delta\underline{\boldsymbol{\Phi}}$ where $\boldsymbol{P}$ is a matrix composed of the eigen-vectors of $\boldsymbol{T}$, $\boldsymbol{D}$ is the diagonal matrix constructed from the corresponding eigen-values, and $\boldsymbol{P}^{-1}$ is the inverse matrix of $\boldsymbol{P}$. Introducing $\delta\underline{\boldsymbol{\Psi}}_i = \boldsymbol{P}_i^{-1}\delta\underline{\boldsymbol{\Phi}}$

for i=1:N as new coordinates of movements, TCM enables cancellation of phase coupling in the system, because of the orthogonality of these vectors, that is $\boldsymbol{\Delta\underline{\Psi}} = \boldsymbol{D}\delta\underline{\boldsymbol{\Psi}}$. Therefore, in the TCM, modifications of the system are applied in direction of $\delta\Psi_i$ to minimize an error function. Each step in the transformed coordinates $\delta\Psi_i$ is operated by calculating the related round-trip phase change of each actuator ($\delta\Phi_i$). This is achieved by evaluating $\delta\underline{\Phi} = P\delta\underline{\Psi}$ at each iteration. Following each step, if progress of error function is along the desire, same steps are repeated till reaching the goal. Otherwise direction of that change is reversed by simply inversing the sign of $\delta\Psi_i$.

3. NUMERICAL SIMULATION

The effectiveness of TCM method was numerically demonstrated on a 3rd order coupled MRR filter shown in Figure 1(a), where 3 actuators are used to modify the round-trip phase Φ_i of each MRR. Proposed tuning methods for this kind of filters exploit sequential sweeping of the individual resonance of each MRR for aligning it to the desired wavelength [1] [2]. Considering equal thermal cross-talk induced by neighbouring MRRs only, the phase coupling matrix $\boldsymbol{T}$ is defined as

$$T = \begin{pmatrix} T_{11} & T_{12} & 0 \\ T_{21} & T_{22} & T_{23} \\ 0 & T_{32} & T_{33} \end{pmatrix},$$

whose eigenvectors $\underline{\boldsymbol{P}_{i1}} = [-1 \quad 0 \quad 1]$, $\underline{P_{i2}} = [1 \quad \sqrt{2} \quad 1]$ and $\underline{P_{i3}} = [1 \quad -\sqrt{2} \quad 1]$ represent the columns of matrix $\boldsymbol{P}$. New coordinates of modifications are calculated by inversing P. The new orthogonal coordinates of modification employed in the TCM are thus as $\delta\Psi_1 = \left[{}^{-1}/_{2} \quad 0 \quad {}^{1}/_{2}\right]\underline{\delta\Phi}$, $\delta\Psi_2 = \left[{}^{1}/_{4} \quad {}^{\sqrt{2}}/_{4} \quad {}^{1}/_{4}\right]\underline{\delta\Phi}$ and $\delta\Psi_3 = \left[{}^{1}/_{4} \quad {}^{-\sqrt{2}}/_{4} \quad {}^{1}/_{4}\right]\underline{\delta\Phi}$. At each iteration, a step is taken in these new coordinates and relevant phase changes of each MRR is calculated using relation $\delta\underline{\Phi} = P.\delta\underline{\Psi}$.

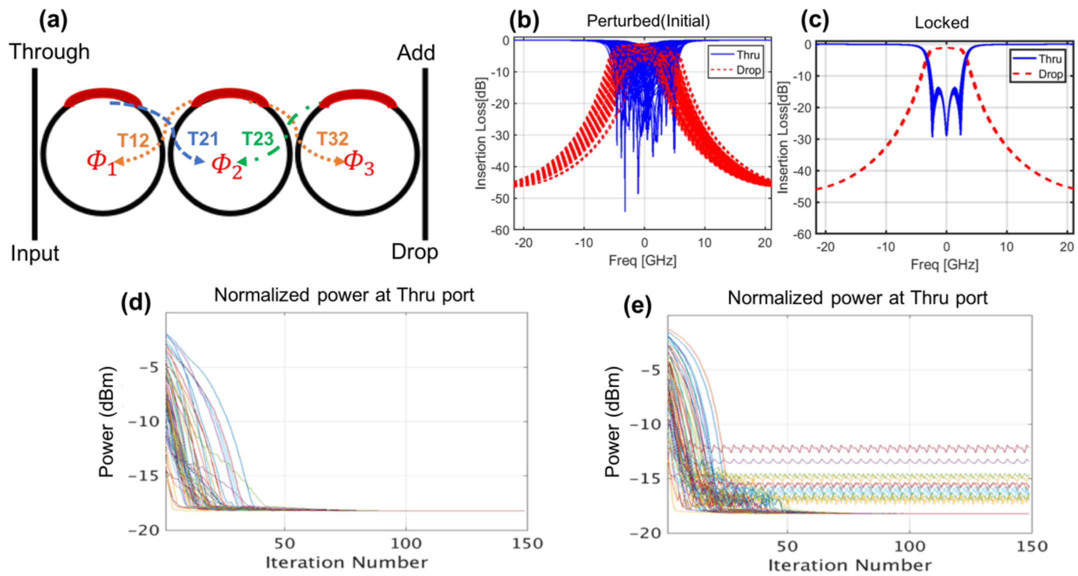

Figure 1 : Numerical simulation of the TCM applied to a **3rd** *order MRR filter (a) with a bandwidth B = 6.5 GHz and FSR = 50 GHz.* $\boldsymbol{\Phi_i}$ *are the round-trip phase of each MRR including thermally coupled perturbations. (b) Through (blue-solid) and Drop (red-dashed) ports of* **3rd** *order MRR filter for 100 cases of random perturbations; (c) Frequency response of the filter after the convergence of the TCM-based algorithm. Normalized power at Through port of the filter during (d) the tuning with TCM and (e) individual tuning of each MRR.*

To evaluate the convergence of TCM, we considered a filter with a free spectral range FSR = 50 GHz and a bandwidth B = 6.5 GHz. Random phase errors as large as ±π/4 (±6.25 GHz) were intentionally introduced in each MRR resulting in the 100 random initial conditions shown in Figure 1(b). The TCM based algorithm was adopted to tune the filter targeting the minimization of the optical power at the Through port, considering at the input port an 5 Gbit/s OOK signal. Figure 1(c) shows that the TCM converged in all the considered cased, enabling fine-tuned filters with almost overlapping frequency responses. Starting from the same perturbed conditions, we compared the convergence curve of the TCM [Figure 1(d)] with the convergence curve achieved by individually controlling the phases of each MRR [Figure 1(e)] using same step size. Many cases of individual control of the MRRs are trapped in oscillation loops due to the phase coupling between resonators. Converged cases of individual tuning in average require more iterations compared to TCM ones.

4. EXPERIMENTAL RESULTS

The TCM-based tuning was experimentally evaluated on a 3rd order MRR based filter fabricated in high-index-contrast silicon oxynitride (SiON) waveguides in Figure 2(a). A 4.4% refractive index contrast platform was employed, enabling the realization of MRRs with up to 100 GHz FSR. The SiON core channel waveguide has a square shape (2.2 × 2.2 μm^2) and is buried in a silica cladding. More details on the waveguide design and fabrication process can be found in [3].

Different initial perturbations were intentionally introduced in every MRR of the SiON filter by applying random errors in the voltages driving the heaters around their optimum tuning point. A frequency spread of the MRR resonances as large as 100 pm (12.5 GHz versus 6.5 GHz BW of the filter) was introduced, as shown in Figure 2(b) presenting the measured Through and Drop port of the perturbed filter. At the input port of the filter a 5 Gbit/s OOK modulated signal with carrier wavelength of 1565.470 nm was used and the TCM was employed to minimize the output power at the Through port. Figure 2(c) shows that, regardless of the initial perturbation, the filter was tuned to the same shape, with a Through port isolation at convergence of 15 dB, corresponding to an estimated residual phase error of π/50.

The TCM was compared to the tuning of each heater individually (hereinafter referred to as "sequential tuning") in terms of convergence ratio and speed. We assumed the same perturbed configurations for the initial state of the filter and we applied both tuning schemes using with the same phase step-size for the heaters. Figure 2(d) shows that sequential tuning of individual resonators may not converge in many cases and a poor isolation with deep oscillations may appear in the steady state. In contrast, the TCM tuning converged in all the considered cases [see Figure 2(e)]. To balance speed and accuracy, an adaptive step strategy was also adopted during the tuning procedure, according to which the phase step-size of the heater is optimized according to the distance from the target point. Results in Figure 2(f) show that the TCM convergence is accelerated by adopting an adaptive phase steps without loss of convergence rate.

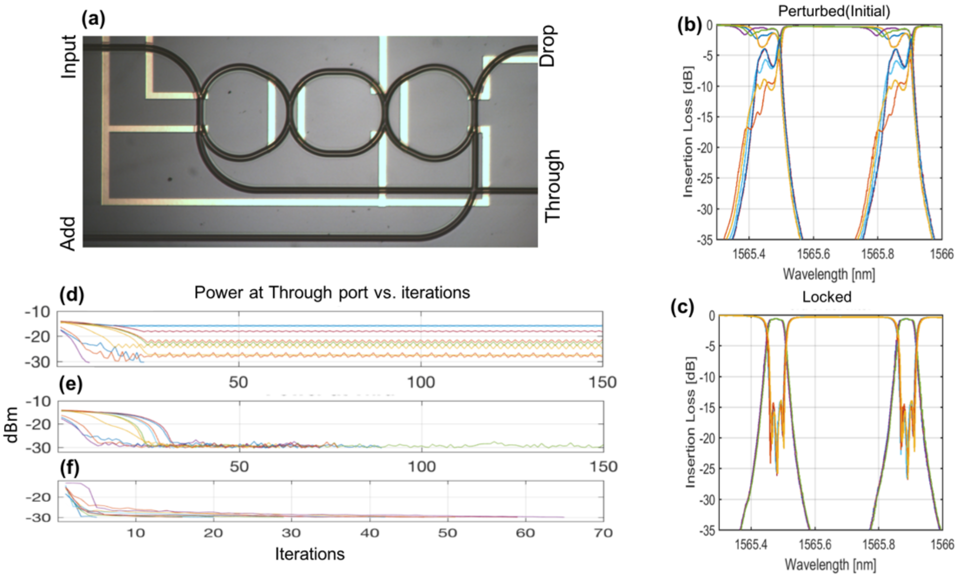

Figure 2: (a) **3rd** *order MRR filter fabricated in SiON technology with FSR = 50 GHz and 3dB B.W. = 6.5 GHz (b)Measured transmission of the Through and Drop port for five randomly perturbed configuration (+/- 100 pm) induced by using thermal phase shifters and (c) after automated tuning performed by using TCM. (d) Measured optical power at Through port of the filter during sequential tuning of individual resonators, exhibiting convergence failure and deep residual oscillations due to thermal crosstalk. (e) TCM tuning shows convergence of the tuning process in all the considered cases. (f) TCM tuning with adaptive phase steps provides faster convergence to the target isolation of the filter without degradation of convergence ratio.*

We also investigated the possibility to exploit the TCM as a wavelength locking algorithm to maintain the fine-tuned status versus time varying perturbations of the system. These perturbations could be variations in power level or wavelength of the input signal, as well as temperature fluctuations across photonic chip. Although temperature variations in integrated photonics are usually controlled by cooling the photonic chip with a TEC, still thermal cross-talk effect take place between photonic components. In a first experiment, starting from a random initial condition of the MRR filter, temperature perturbations were intentionally introduced by acting on the TEC underneath the sample while the TCM based tuning was executing. Figure 3(a) shows the evolution of heater voltages and Through port power during the temperature compensation process. Temperature was increasing even during the tuning process, but the algorithm prevented power fluctuation at Through port due to this perturbation. In the experiment of Figure 3(b), the perturbation is given as a continuous wavelength drift of the input signal as large as 60 pm (equivalent to 7.5 GHz) in 30 seconds. Observing the power at Through port, a small variation due to this perturbation is traceable. Even though wavelength drift was introduced during the compensation, a robust solution is obtained. In another experiment, the perturbation was introduced as a sudden 10 pm shift in centre wavelength of the signal. Comparing the eye diagram of the output signal at the Drop port of filter in case of active TCM locking Figure 3(e) and without locking Figure 3(d) to the eye diagram of the input signal (c), the effectiveness of the wavelength locking algorithm is evident.

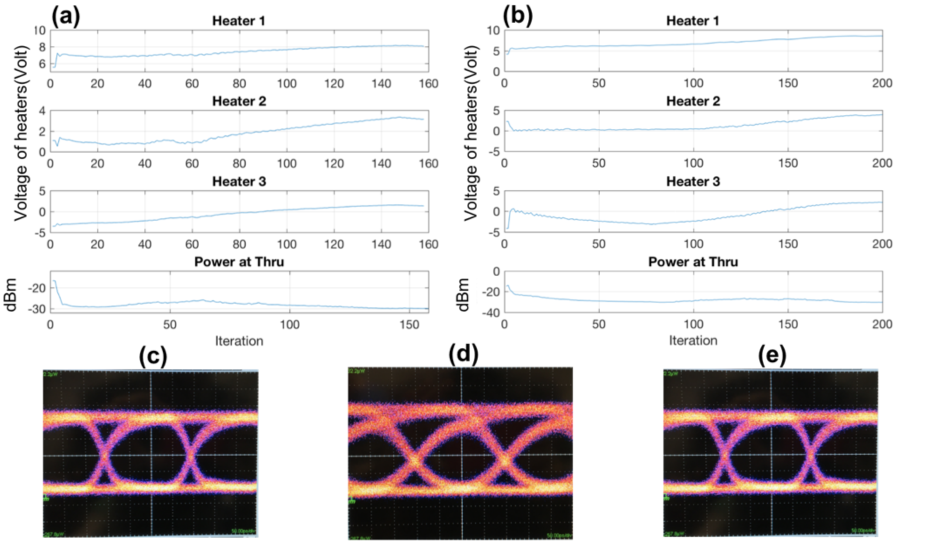

Figure 3: Wavelength locking of the 3rd order SiON MRR filter using the TCM method: (a) Locking against 3 degrees of chip temperature drifts. Panels show the voltages of heaters (first 3 curves from top starting from -5 volt) and the optical power at Through port during the tuning and locking of the filter. (b) Locking against a continuous change in the wavelength of the input signal (60 pm shift in 30 seconds). (c) Eye diagram of a 5 Gbit/s OOK signal at the input port of the filter; eye diagram of the dropped signal (d) after introduction of 10 pm jump in the signal wavelength and (e) after filter locking with TCM-based method.

5. CONCLUSIONS

We demonstrated that the TCM method presented in this work effectively cancel phase coupling due to thermal crosstalk in PIC. The effectiveness of the TCM is proved through numerical simulations and experimental results on coupled MRR filters in SiON technology, demonstrating faster and more robust convergence with respect to conventional approaches based on the individual control of each MRR. The TCM can be used to implement both tuning schemes for PIC reconfiguration and wavelength locking algorithms, to counteract temperature drift of the photonic chip or to track random fluctuations of the wavelength of the input signal. Performance can be further improved by adopting a dedicated controller (like an FPGA) to decrease loop latency. Finally, the TCM can be applied to generic PIC architectures based on arbitrary combinations of MRRs and other integrated interferometric devices.

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REFERENCES

[1] Hasitha Jayatilleka, Kyle Murray, Miguel Ángel Guillén-Torres, Michael Caverley, Ricky Hu, Nicolas A. F. Jaeger, Lukas Chrostowski, and Sudip Shekhar , “Wavelength tuning and stabilization of microring-based filters using silicon in-resonator photocond,” *Opt. Express,* 2015.

[2] J. C. C. Mak and W. D. Sacher and T. Xue and J. C. Mikkelsen and Z. Yong and J. K. S. Poon , “Automatic Resonance Alignment of High-Order Microring Filters,” *IEEE Journal of Quantum Electronics, vol. 51, no. 11, pp. 1-11, Nov. 2015.,* pp. vol. 51, no. 11, pp. 1-11, Nov. 2015..

[3] 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.