A tuning method for photonic integrated circuits in presence of thermal cross talk

(Student Paper)

Maziyar Milanizadeh[1,], Douglas Aguiar[1,], Sara Ahmadi[1,], Francesco Morichetti[1,], Andrea Melloni[1,]
[1]*Dipartimento di Electtronica Informazione e Bioingegneria -*
Politecnico di Milano, Piazza Leonardo da Vinci, 32 - 20133 Milano - Italy
Tel: +39223998979, e-mail: maziyar.milanizadeh@polimi.it

Abstract

We present a novel method to perform tuning and locking of photonic integrated circuits (PICs) in presence of thermal cross-talk. The unwanted phase coupling among different elements of the circuit is canceled via exploiting the eigen-vectors of the thermally coupled system. The effectiveness of the proposed method is proved on PIC architectures, based on microring resonators (MRRs) and Mach-Zehnder interferometers (MZIs).

Keywords: Tuning, Locking, Resonance alignment, Thermal cross-talk, phase coupling, Microring resonators

1 INTRODUCTION

In photonic integrated circuits (PICs), fabrication tolerances appear in the form of phase errors. Owing to the sensitivity of the effective index of the optical waveguides to nanometer-scale dimensional variations, these effects are particularly pronounced in high index contrast photonic platforms. Furthermore, phase drifts may be also caused during the device operation by temperature changes introduced in neighboring systems on the same chip.

Thermal actuators integrated in optical waveguides are a well-established approach to compensate against phase errors and to reconfigure the PIC responses. However, mutual thermal crosstalk between neighbour waveguides of the same PIC or among different PICs integrated onto the same chip may cause unwanted phase perturbations and impair control procedures. This phenomenon leads to increase of required iterations or even divergence in control algorithms employed to modify or maintain a status of the device.

In this contribution we present a novel method, named *Transformed Coordinate method* (TCM), that can be used to circumvent thermal cross talk effect and allows to automatically configure and stabilize PICs with no penalties introduced by thermal coupling between different actuators. The effectiveness of the proposed method is demonstrated by numerical simulations and experiments carried out on different PIC architectures, based on different arrangements of microring resonators (MRRs) and Mach-Zehnder interferometers (MZIs).

2 TRANSFORMED COORDINATE METHOD

To illustrate the TCM, let us consider the scheme of Fig. 1(a) showing an arbitrary integrated optic device with N thermal actuators for reconfiguration and tolerance compensation. When an electrical signal 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 it 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 too. The actual phase shift $\Delta\phi_i$ induced in each waveguide is thus given by the phase coupling matrix:

$$\begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \Delta\phi_3 \\ \vdots \\ \Delta\phi_n \end{pmatrix} = \begin{pmatrix} 1 & \mu_{12} & \mu_{13} & \cdots & \mu_{1n} \\ \mu_{21} & 1 & \mu_{23} & \cdots & \mu_{2n} \\ \mu_{31} & \mu_{32} & 1 & \cdots & \mu_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mu_{n1} & \mu_{n2} & \mu_{n3} & \cdots & 1 \end{pmatrix} \begin{pmatrix} \delta\phi_1 \\ \delta\phi_2 \\ \delta\phi_3 \\ \vdots \\ \delta\phi_n \end{pmatrix} \tag{1}$$

where the phase coupling coefficient μ_{nm} between the $m-th$ actuator and the $n-th$ waveguide depends on the PIC topology. Due to this phase coupling, individual modification of phases $\delta\phi_i$ is not an effective method for controlling the system, because the vector $\delta\phi$ of the desired phase shift is perturbed via this mapping matrix.

To counteract phase coupling, the TCM exploits the eigen-modes of the thermally coupled PIC. Mathematically this means that the phase change vectors that are utilized, correspond to the eigen-vectors of the unwanted phase coupling matrix extracted from (1). Orthogonality of these vectors enable to apply decoupled phase modification to the system, as shown in Fig. 1 . In principle, if the phase coupling coefficients μ_{nm} in a system of N elements are all known, TCM can reaches the optimum point in only N operations.

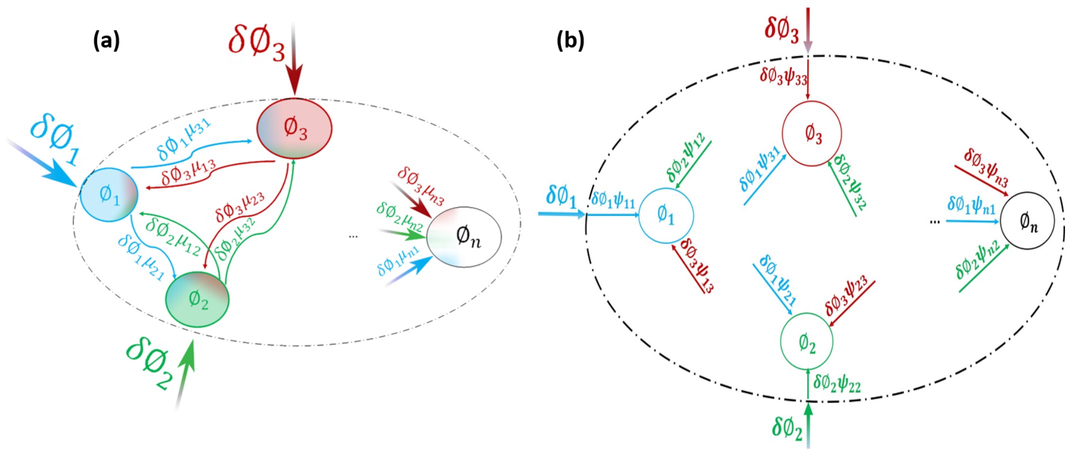

Figure 1. **(a)** Schematic representation of a PIC in the presence of phase coupling due to thermal crosstalk. $\delta\phi_i$ is the desired phase change and $\Delta\phi_i$ is the actual one. **(b)** Phase de-coupling achieved by applying TCM in control of the PIC. $\psi_{j,i}$ is the $j-th$ eigen-vector applied to $i-th$ actuator phase change $\delta\phi_i$

2.1 Numerical simulations

To show the effectiveness of the TCM method, we present its use on two different PIC architectures. The first one is the 3rd order coupled MRR filter shown in Fig. 2.(a), where 3 actuators are used to modify the round trip phase ϕ_i of each ring. 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] and are therefore vulnerable to phase coupling effects. In TCM all the MRRs are simultaneously modified. Considering only thermal cross-talk induced by neighboring MRRs, the thermally-coupled system can be modeled as

$$\begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \Delta\phi_3 \end{pmatrix} = \begin{pmatrix} 1 & \mu & 0 \\ \mu & 1 & \mu \\ 0 & \mu & 1 \end{pmatrix} \begin{pmatrix} \delta\phi_1 \\ \delta\phi_2 \\ \delta\phi_3 \end{pmatrix} \tag{2}$$

Phase changes are applied sequentially but according to the eigenvectors of unwanted phase coupling matrix. These eigen-vectors are $\psi_{1,i} = [-1, 0, 1]$, $\psi_{2,i} = [1, \sqrt{2}, 1]$, $\psi_{3,i} = [1, -\sqrt{2}, 1]$ respectively with $i = 1, 2, 3$. To test the convergence of the TCM, we considered a randomly perturbed filter, where phase errors as large as

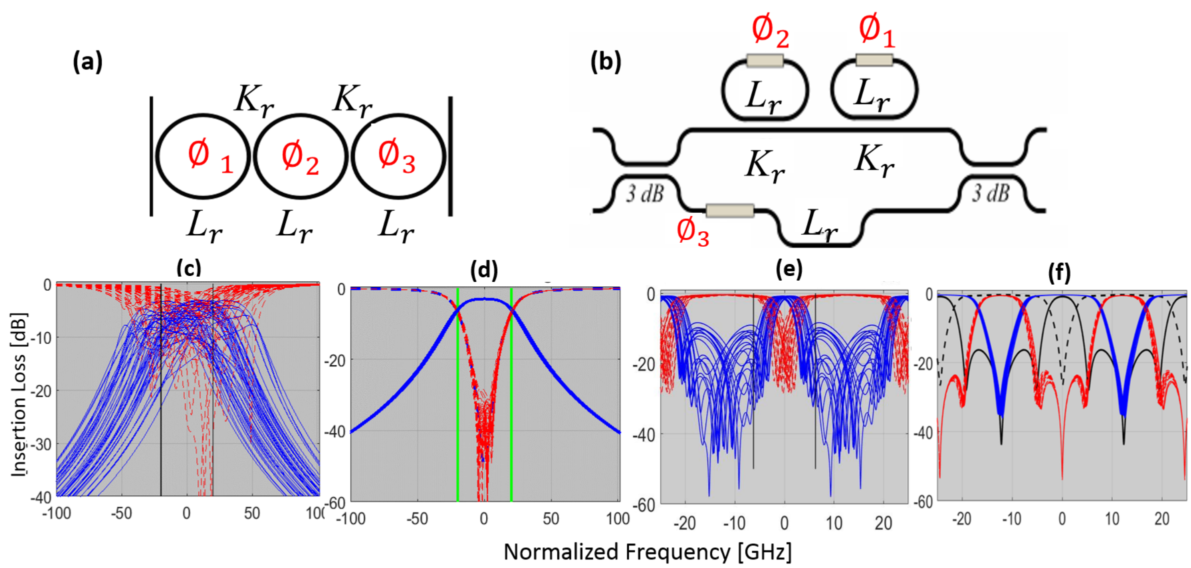

Figure 2. **(a)** 3^{rd} order MRR filter, $40GHz$ BW and $1THz$ of FSR where ϕ_i are the round trip phase of each rings. **(b)** Unbalanced Mach-Zehnder loaded with two rings to perform as tunable bandwidth filter with FSR of $25GHz$ and BW tune-ability of 0.1*FSR-0.9*FSR **(c)** Through (red-dashed) and drop(blue-solid) ports of 3^{rd} oder MRR filter for 50 cases of random perturbations. **(d)** Through and drop ports of 3^{rd} order MRR filter tuned using TCM **(e)** Bar (blue-solid) and cross (red-dashed) port of tunable Bandwidth filter for 30 cases of random perturbations as initial status of simulations. **(f)** Filters started from fig(e) are tuned and adapted to wider signal. Black curves shows tuned filter for narrow signal

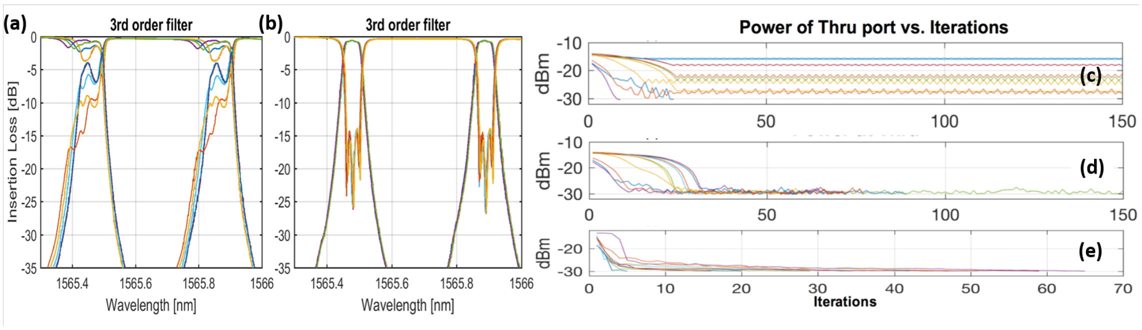

Figure 3. Experimental tuning based on the transform coordinate method. Frequency domain response of **(a)** a randomly perturbed 3^{rd} order MRR filters in SiON technology (through and drop ports) and of **(b)** the filter after TCM-based tuning. Optical power at through port of the filter during **(c)** conventional sequential tuning of resonators, **(d)** TCM with constant phase steps and **(e)** TCM with adaptive phase steps.

$\pm\pi/16$ ($\pm 31GHz$ versus $40GHz$ of filter BW) were deliberately introduced in each MRR (50 random initial conditions shown in Fig.2.(c)). Using the algorithm to minimize the optical power at the through port, fine tuned filters with almost overlapping frequency responses were achieved in all the cases of study [see Fig.2.(d)].

The second PIC architecture is an unbalanced MZI loaded with two MRRs in the shorter arm, this architecture implementing a tunable bandwidth filter [3]. Bandwidth tuneability is achieved by controlling the three phase shifters ϕ_i. The tuning of $\phi_1 - \phi_2$ allows the control of the 3 dB bandwidth of filter while the condition $\phi_3 = m\pi + (\phi_1 + \phi_2)/2$ allows the filter transfer function to be always symmetric with respect to filter central frequency. Considering all the actuators to introduce same mutual thermal cross-talk to each other, the phase coupling matrix is given by

$$\begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \Delta\phi_3 \end{pmatrix} = \begin{pmatrix} 1 & \mu & \mu \\ \mu & 1 & \mu \\ \mu & \mu & 1 \end{pmatrix} \begin{pmatrix} \delta\phi_1 \\ \delta\phi_2 \\ \delta\phi_3 \end{pmatrix} \tag{3}$$

By distinguishing the unwanted phase coupling matrix, eigen-vectors are calculated as $\psi_{1,i} = [-1, 1, 0]$, $\psi_{2,i} = [-1, 0, 1]$, $\psi_{3,i} = [1, 1, 1]$ respectively with $i = 1, 2, 3$. In this example we start from a tuned filter for a specific channel (black curves in Fig.2.(e,f)). Random phase errors are introduced in ϕ_i as large as $\pm\pi/10$ ($\pm 1.25GHz$ versus $5GHz$ BW of filter). When the signal bandwidth is increased, not only the algorithm compensates the perturbations, but it adapts the filter to the broader signal bandwidth. Blue curves in Fig.2.(f) show transfer function of converged filters which is adapted to the wider signal bandwidth.

3 EXPERIMENTAL RESULTS

The TCM-based tuning was experimentally tested on a 3rd order MRR based filter fabricated in high-index-contrast silicon oxynitride (SiON) waveguides [4]. Different initial perturbations were intentionally introduced as random errors in the voltages driving the heaters around their optimum tuning point, resulting in a resonance spread as large as $100pm$ ($12.5GHz$ versus $6.5GHz$ BW of the filter). Fig.3.(a) shows through and drop port of the perturbed filter. By applying the TCM to minimize the power in through port at 1565.47 nm, the filter was tuned to the same shape regardless of the initial condition, as shown in Fig.3.(b).

Fig.3.(c) shows that sequential tuning of individual resonators may not converge in many cases. In contrast, the TCM tuning converged in all the considered cases, as shown in Fig.3.(d). Results in (e) show that the TCM convergence is accelerated by adopting an adaptive phase steps, leading to a reduction in the required iterations.

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