

Thermal Crosstalk Modeling and Compensation for Programmable Photonic Processors

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Abstract—We quantify thermal crosstalk in a programmable photonic processor and present both analytical and data-driven models. We experimentally demonstrate model-based predictive crosstalk compensation for a microring resonator realized on a pre-calibrated chip, making it possible to tune the resonance wavelength with ± 0.5 picometer accuracy.

Keywords—Programmable photonics, photonic processors, thermal crosstalk, machine learning

I. INTRODUCTION

Programmable photonic processors are photonic integrated circuits (PICs) that can be reprogrammed to perform various functions as needed, such as implementing tunable wavelength filters or linear optical accelerators [1]. These processors rely on optical devices such as Mach-Zehnder interferometers (MZIs) and microring resonators (MRRs), where the individual performance is influenced by phase perturbations, which can impact the overall behavior of the PIC. In order to achieve programmability and scalability, a well-established approach relies on thermo-optic low-loss phase shifters [2]. However, even when errors due to fabrication tolerances are accounted for using accurate calibration routines, modeling and compensating for thermal crosstalk remains a difficult challenge to tackle despite its deterministic nature [2, 3].

In this work, we experimentally quantify the wavelength shift caused by thermal crosstalk for the spectral response of a MRR implemented on a programmable photonic chip. We train two models relating the phases driven on all actuators on the PIC to the wavelength shift: (i) a physics-based analytical model and (ii) a data-driven machine learning model. Finally, we experimentally demonstrate model-based predictive crosstalk compensation by adjusting the phase shifters on the MRR itself.

II. THERMAL CROSSTALK IN PHOTONIC PROCESSORS

A. Experimental Setup

In order to quantify the effect of thermal crosstalk, we implemented a simple MRR filter on a commercially available programmable photonic processor with a hexagonal waveguide mesh, shown in Fig. 1. Each rectangle denotes a programmable unit cell (PUC), which is a MZI with two thermo-optic phase shifters, one on each arm. All 142 phase shifters were calibrated automatically using the procedure described in [4], meaning that each PUC can accurately be controlled to realize a given coupling factor and relative phase delay, individually.

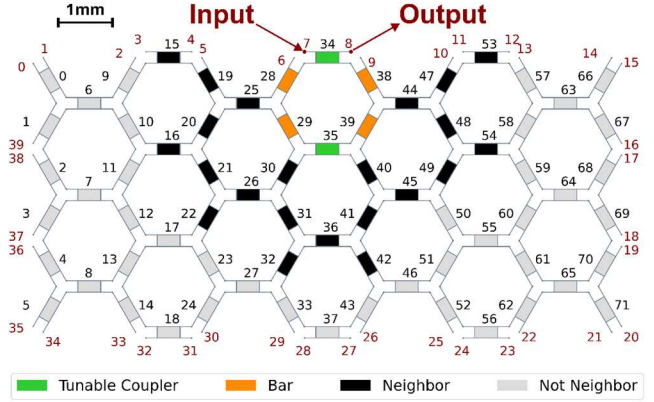


Fig. 1. Schematic of the 72-PUC waveguide mesh with the microring filter. Only the neighboring PUCs were used for the compensation experiment. Red numbers are for input/output ports and black numbers are for PUC indices.

Six PUCs were programmed to form an add-drop filter with a free spectral range of 118.4 pm. PUC 34 was used to couple to the optical input/output through ports 7 and 8. PUC 35 was only used to maintain a high extinction ratio. No change in the coupling ratios of the PUCs was measured despite thermal crosstalk, as both phase shifters in a PUC are affected similarly from crosstalk due to their vicinity.

In the presence of thermal crosstalk, increasing the temperature around the ring results in a higher optical signal delay, which in turn produces a red shift in the output spectrum. Simply applying a phase shift within $[0, 2\pi]$ to one of the neighboring PUCs produces negligible effects on the position of the resonance, well below our setup resolution of 3 pm. Therefore, both phase shifters in all 66 remaining PUCs were tuned simultaneously to different random values within $[0, 2\pi]$ and the resulting spectra were measured. The wavelength shift due to crosstalk was calculated after upsampling the measured spectra through spline interpolation. 250 different measurements were performed and an 80%-20% split for training and testing was used for model training and evaluation.

B. Modeling Approaches

The crosstalk-induced wavelength shift ($\Delta\lambda$) increases linearly with the phase shift driven on a neighboring PUC (ϕ_i) and decreases with distance to the PUC (d_i) [5], which are both captured by the analytical model given in (1):

$$\Delta\lambda = \sum_i (p_1 e^{-p_2 d_i} + p_3 d_i + p_4) \phi_i \quad (1)$$

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Note that p_i ($i = 1, \dots, 4$) are fitting parameters trained using experimental measurements. This model is a weighted summation of the phases where the weights depend on the distances to the ring. Employing a more data-driven approach, we can set $p_1 = p_2 = p_3 = 0$ to remove the dependence on d_i and instead fit a different $p_{4,i}$ separately for each PUC i , which we call the weights a_i , resulting in the model given in (2):

$$\Delta\lambda = \sum_i a_i \phi_i + b \quad (2)$$

Both the weights a_i and the bias b were trained using ridge regression, where the regularization parameter was optimized using five-fold cross validation. Both models were trained to minimize the root-mean squared error (RMSE) between the experimentally measured and the predicted wavelength shifts.

III. EXPERIMENTAL RESULTS

After training using the training set, training RMSEs of 0.55 and 0.43 pm was achieved, which resulted in testing RMSEs of 0.55 and 0.50 pm for the analytical and data-driven models, respectively. Note that the analytical model has 4 degrees of freedom while the data-driven one has 67 (66 weights + bias). Evolution of $\Delta\lambda$ with PUC distance is shown in Fig. 2 for the analytical model. A major advantage of the analytical model is that it can extrapolate to PUC distances not present in the chip, providing valuable insight for future chip designs with more densely packed PUCs, assuming the model still holds.

The weights found after training the regression model are shown in Fig. 3. A major advantage of this model is that it does not require precise knowledge of the chip layout. While the model is lacking in interpretability compared to the analytical one, the inverse correlation between the weights and the PUC distances show that the black-box approach produces physically sound results. Note that the weights are mostly within 0.1 and 0.5 pm/ π , which is in agreement with the analytical model. This means that the ratio between the phase due to crosstalk and the driven phase ranges from 1:1200 to 1:240 based on distance.

Finally, in order to demonstrate predictive crosstalk compensation, we drove the phase shifters on the 22 PUCs closest to the ring (shown in Fig. 1) to $\phi = \pi$ and 2π , then used the analytical model to predict the wavelength shifts. The phase shifters on the ring were adjusted to counteract the effect of thermal crosstalk, as shown in Fig. 4. After compensation, both wavelength shifts were measured to be less than 0.5 pm. Similar results were obtained using the data-driven model.

IV. CONCLUSION

We present and experimentally evaluate two models for thermal crosstalk in a programmable photonic processor. Once the chip has been calibrated, our models use the phases driven to the actuators and accurately predict the wavelength shift for a microring filter realized using the chip. Furthermore, we show that the effect of thermal crosstalk can be accounted for using the phase shifters on the ring itself. While the effect of thermal crosstalk was measured to be negligible under practical operating conditions due to optimized design, crosstalk compensation can enable highly phase-sensitive applications and future more compact chip designs.

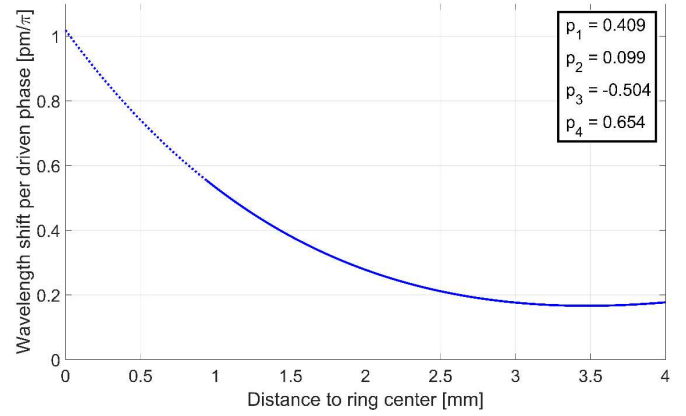


Fig. 2. Analytical model after fitting with optimal parameters shown in the box. Dashed portion indicates PUC distances not present in chip under test.

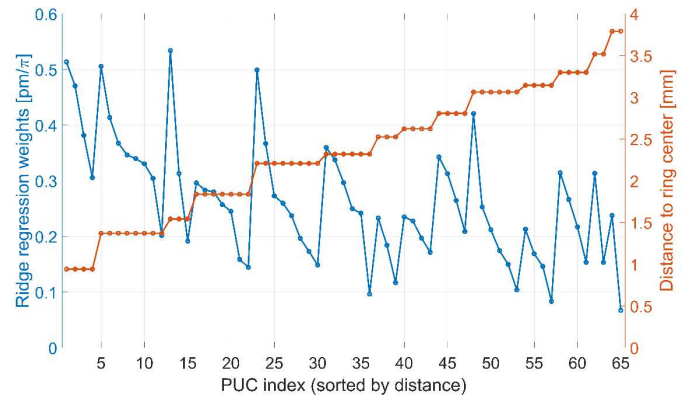


Fig. 3. Weights found by ridge regression plotted alongside the distance to ring center for each PUC. The two are inversely correlated with $\rho = -0.53$.

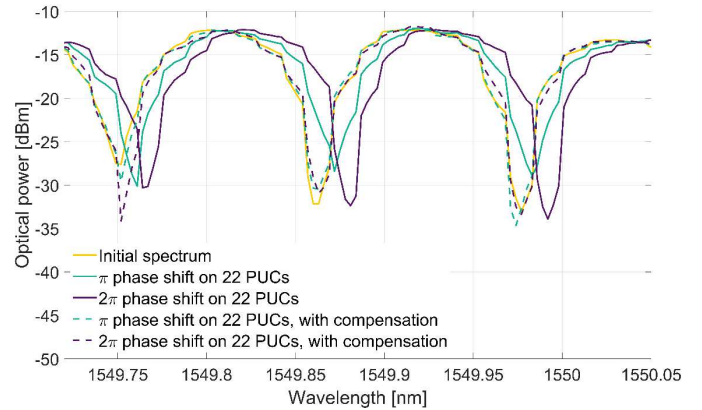


Fig. 4. Spectral measurement of the ring under test before and after thermal crosstalk compensation.

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