Automatic Tuning of Vernier Microring Filters Using Comprehensive Characterization Models and Hybrid Optimization Algorithms

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Abstract: An efficient approach to automatically configure and tune Vernier microring filters by utilizing hybrid optimization algorithms and robust characterization models is presented. Automatic tuning of a four-ring Vernier filter over the entire C-band is experimentally demonstrated to evaluate this method.

1. Introduction

Microring-based silicon photonics integrated optical filters are becoming increasingly attractive for next-generation Data Center Interconnect (DCI) networks and telecommunication applications, to reduce optical amplifier noise from neighboring Dense Wavelength Division Multiplexing (DWDM) channels in otherwise filter-less systems. Due to their small footprint, preferable spectral features and good performance, such filters are an elegant and cost-effective way to improve DWDM system performance significantly. Series-coupled Vernier microring filters in particular are very appealing, since they offer wide free spectral ranges (FSRs) with feasible and practical thermal tuning requirements. However, the deployment of such devices in commercial products is still limited, mostly due to thermal, performance and control challenges.

Over the past decade, many techniques were demonstrated to address these challenges, including Automatic Resonance Alignment and Tuning (ARAT) algorithms [1–3], control methods, and configuration recipes [4, 5]. To increase the efficiency and robustness of single and multi-variable ARAT algorithms used in [1–3], Thermal Eigenmode Decomposition (TED) method was proposed to reduce the impact of thermal crosstalk on the overall performance of ARAT algorithms [4]. Furthermore, in-resonator photoconductive heaters (IRPHs) were proposed to reduce control and tuning complexity of series-coupled and high-order microring filters [6, 7]. However, their practical use is limited to applications where high insertion loss (IL) can be tolerated.

In this paper, we present a new technique to improve the efficiency and configuration speed of such devices by implementing multi-variable hybrid optimization algorithm, which is customized based on automatic thermal characterization of the device and utilizes constrained adaptive derivative-based and derivative-free optimization algorithms. This technique insures avoiding local optima traps by continuously changing the applied algorithm between constrained derivative-free direct search algorithm and nonlinear constrained derivative based algorithm, which uses Sequential Quadratic Programming (SQP) methods. The dynamic selection of the algorithm is based on the current noise level of the detected signal and heuristics. A comprehensive model using simulations in addition to optical and electrical measurements is implemented to evaluate thermal crosstalk optimization variables' bounds. This approach increases the efficiency and convergence rate of the optimization algorithm while reducing the stress applied on the heaters and life-time degradation. Limiting the maximum applied current and heater temperature to the minimum values required to tune each ring across approximately a full FSR reduces the total number of function evaluations needed to reach the global optima. We implement this technique to demonstrate the automatic configuration and tuning of two-stage second- and high-order Vernier microring filters over the C-band.

2. Device Configuration and Characterization

Fig. 1(a) shows the fabricated Vernier filters on silicon-on-insulator (SOI) platform. Devices fabricated include two-stage second-order, third-order, and fourth-order Vernier filters, a two-stage second-order Vernier filter with silicon substrate undercut, and a two-stage second-order microring Vernier wavelength-independent filter based on broadband silicon photonic directional couplers [8]. The lengths of the ring resonators were chosen in all designs such that the effective FSR is 40 nm, with a minimum resonator length of 121.34 μm to limit the maximum individual FSR of each ring to 5 nm and reduce the heater temperature required to achieve 2π phase shift. Fig. 1(b) shows a schematic diagram of the proposed approach to tune the filters. A comprehensive simulation model is used to obtain initial data to customize the initial optimization algorithm, including a 3-D thermal-conductive model to estimate thermal crosstalk and required heater powers as shown in Fig. 1(c), which demonstrates a thermal model

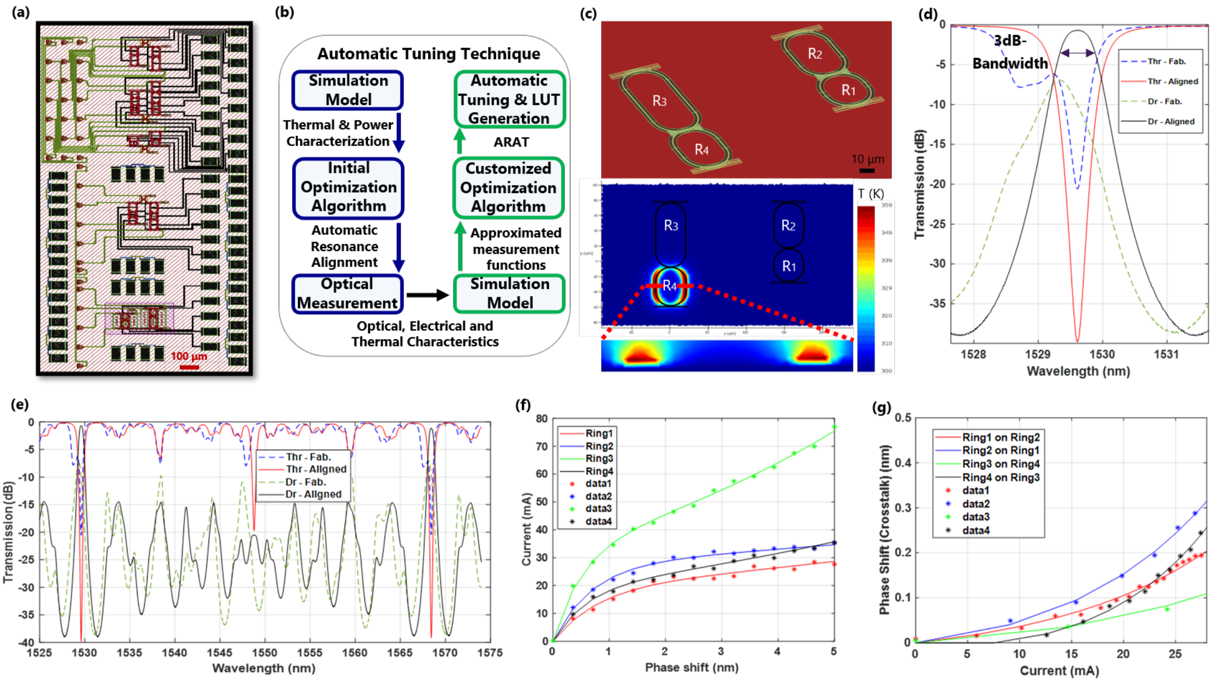

Fig. 1: (a) The layout of the fabricated microring Vernier filters. (b) A schematic diagram of the automatic tuning technique. (c) A demonstrative figure for the 3-D thermal-conductive simulation model. (d) Normalized drop- and through-port spectra of the peak transmission. (e) Normalized drop- and through-port spectra over a full FSR within the C-band (Normalization is to the input-output grating coupler spectra of a reference loop) (f) Extracted required heaters' currents as functions of nominal phase shifts. (g) Extracted crosstalk phase shifts as functions of heaters' currents.

for the fabricated two-stage second-order Vernier filter. An automatic calibration step is performed to feed the simulation model with more accurate data to customize the hybrid optimization algorithm, which can then be used to automatically and actively tune the filter or generate Lock-Up-Tables (LUTs). The calibration starts by running the initial optimization algorithm to align the resonances of the rings at the desired laser wavelength. After the initial resonance alignment, the wavelength is scanned across the tuning range multiple times using EXFO laser and optical component tester while applying different voltages for only one of the rings at each time. The measured spectra of all scans is fed to the model, which extracts optical, thermal and electrical properties, including fitted nominal and crosstalk phase shifts as functions of current or voltage. This approach can be implemented for all mentioned filter architectures by monitoring only the final output power of the device, irrespective of the number of stages and coupled rings. Using power taps to monitor the power after each stage only decreases the calibration time, which is not critical since this step is performed only once. Although the calibration step increases the efficiency and robustness of the ARAT by reducing the number of function evaluations needed to tune the filter, particularly for high-order filters, the initial hybrid optimization algorithm is sufficient for efficient ARAT compared to what was previously reported for similar devices [1–5]. Fig. 1(d) and (e) show the drop and through-port spectra of the wavelength-independent two-stage second-order filter as fabricated and after applying the initial hybrid optimization algorithm. Fig. 1(f) shows the fitted extracted required heaters' currents as functions of nominal phase shift, while Fig. 1(g) shows crosstalk phase shifts of all rings as functions of heaters' currents. Thermal crosstalk between the two stages is found to be negligible, however, thermal crosstalk between coupled-rings within the same stage is significant. These extracted functions can be used to estimate initial searching points for the algorithm to improve the convergence rate.

3. Evaluation of the Automatic Tuning Technique

To test and evaluate the efficiency of the proposed tuning method, the device was tuned to over 60 different frequency channels across the C-band. Fig. 2(a) shows the tuned spectra using extracted heaters' functions without running the customized hybrid optimization algorithm. Although the tuned spectra are not at the optimal state, this initial tuning can be used as a starting point for the customized hybrid optimization algorithm to increase efficiency, convergence and tuning speed significantly. Fig. 2(b) shows the tuned spectra using the hybrid optimization algorithm, where it can be seen that tuning converged to the optimal state for each wavelength channel, despite noise and thermal crosstalk. On the other hand, implementing only constrained derivative-free algorithms diverged at several wavelength channels as shown in Fig. 2(c), which demonstrates the convergence rate when applying derivative-free algorithms with constraints on the optimization domain. Fig. 2(d) represents a performance comparison in terms of convergence rate and number of function evaluations needed to reach the optima to tune the filter resonance to 1550 nm. Using the initial hybrid optimization algorithm or the customized one based on extracted heater functions show two and three times faster convergence rate, respectively, compared to the simple derivative-free optimization algorithm. Fig. 2(e) and (f) represent the variation of the 3 dB-Bandwidth and IL of the peak transmission, respectively, when tuned to these channels using the hybrid optimization algorithm, extracted heater functions, and simple derivative-free optimization algorithm. It can be noticed that the hybrid optimization algorithm has the lowest deviation in 3 dB-bandwidth and IL, limited in this measurement to $\pm$ 2.7 GHz and 0.3 dB, respectively. Tuning using extracted heater functions shows large deviation in both 3dB-bandwidth and IL, however, it doesn't fail to converge. On the other hand, the derivative-free optimization algorithm shows lower deviation in both 3 dB-bandwidth and IL, when neglecting few outliers due to divergence, with $\pm$ 7.1 GHz and 2.8 dB deviation, respectively. The average number of function evaluations needed to reach the optima using hybrid optimization algorithm for the four-ring filter is 65 $\pm$ 10, which demonstrates the efficiency of this method.

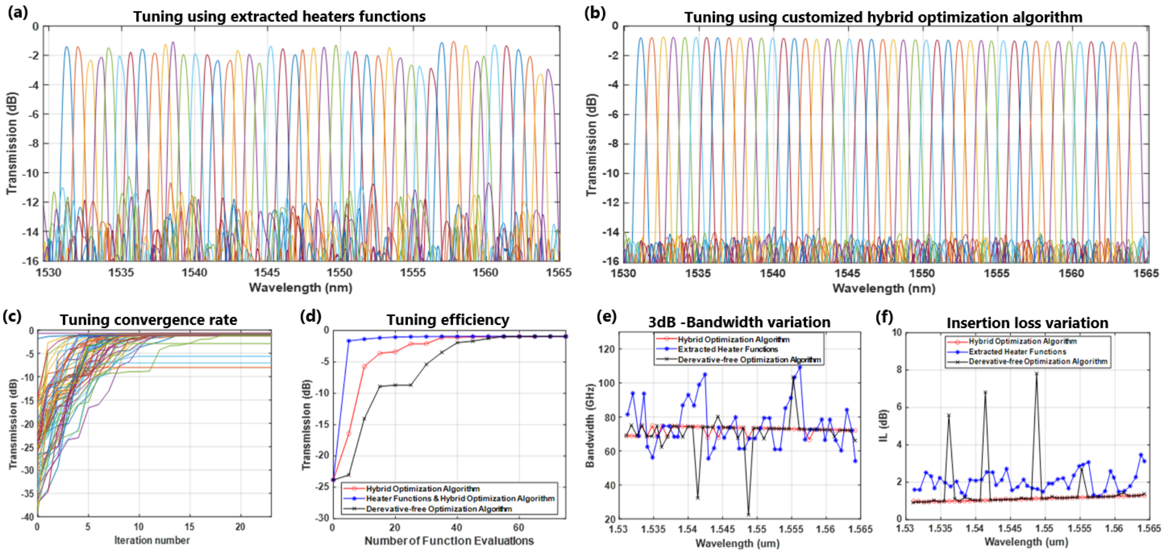

Fig. 2: (a) Tuned spectra using extracted heater functions. (b) Tuned spectra using customized hybrid optimization algorithm. (c) Convergence rate when implementing constrained derivative-free optimization algorithms. (d) Convergence rate comparison at 1550 nm. (e) and (f) Variation of the 3 dB-Bandwidth and IL of the peak transmission, respectively.

4. Conclusions

An effective method to automatically tune silicon photonic integrated microring Vernier filters is presented. The approach employs hybrid optimization algorithms to improve convergence speed and overcome thermal crosstalk and noise in real systems. This technique was implemented to automatically configure and tune a four-ring two-stage second-order Vernier filter over the C-band to experimentally demonstrate the feasibility of the concept.

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