Tuning and locking of integrated optical filters and circuits

(Invited Paper)

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***Abstract*—Complex photonic circuits require advanced design and control tools to ensure their proper functionality even when subject to uncontrollable fabrication uncertainties and non-idealities. Here we show the use of optimization techniques to increase the robustness of a design to tolerances and an advanced tuning strategy to accurately control a fabricated photonic filter.**

I. Introduction

The evolution towards complex photonic circuits, that could integrate hundreds of building blocks and functionalities, poses major issues both on the design and on the control of the circuits in real operation conditions. From the design point of view, advanced circuits require to take into account non-idealities and fabrication uncertainties directly during the design stage to evaluate their impact on the circuit behaviour and optimize the design in order to increase the robustness of the parameters of interest to stochastic fluctuations. On the other hand, in real operative conditions, optical and thermal cross-talk, spurious effects, and drifts, can anyway prevent the realized circuits to work as expected. Advanced photonic devices must hence be considered as a system that must be controlled through feedback loops and proper algorithms. In this contribution, both optimization (performed during the design, before the fabrication of the devices) and control strategies (applied on the realized devices) are discussed. Advanced stochastic techniques are exploited to investigate the impact of fabrication tolerances on the bandwidth of photonic filter and to optimize the design to improve the performance. Further, the tools needed to monitor and control a complex circuit are described, presenting the experimental results obtained on the tuning of coupled microring resonator filters.

II. Optimize before fabrication: design optimization

The possibility to access stochastic information on building blocks variability during the design, allows to predict the behaviour of the realized circuit in advance exploiting standard techniques such as Monte Carlo [1] or more advanced tools as Polynomial Chaos Expansion [2]. As an example, Fig.1 (a) shows the Monte-Carlo analysis of the transfer functions of a fifth-order coupled resonator filter (SOI technology) at the drop and through ports when exposed to fabrication uncertainties. The nominal filter design was obtained with a standard synthesis technique for Chebyshev filters and the designed ideal transfer functions are reported for comparison, with solid red and dashed blue lines, respectively. The resulting coupling coefficients for the six directional couplers are K1 = K6 = 0.337, K2 = K5 = 0.024, K3 = K4 = 0.012. With this values the filter has a nominal bandwidth of 25.6 GHz and an off-band isolation at the drop port of 26 dB. All the five rings have the same length of 336.2 μm and the same the effective index of 2.23. The nominal gap distance of the waveguides in the five coupling regions is 0.3 μm. In order to describe realistic fabrication uncertainties, random fluctuations are considered for both effective index of the waveguides ($\sigma = 10^{-5}$) and gap of the directional couplers (σ = 5 nm). Simulations were performed with the commercial circuit simulator Aspic [3]. Grey curves represent the obtained behaviour in 100 simulation runs. As can be seen, the transfer function can be rather different from the expected one, affecting both isolation and bandwidth of the filter. Figure 1 (b) shows in black line the probability density function (pdf) of the 3-dB bandwidth. As can be seen, the pdf is centred at the nominal value (25.6 GHz) but the bandwidth of the fabricated devices is expected to fluctuate of at least $\pm$1 GHz.

Beside investigating the effects of uncertainties on the transfer function of a circuit, the availability of statistical information and realistic models allows to apply optimization

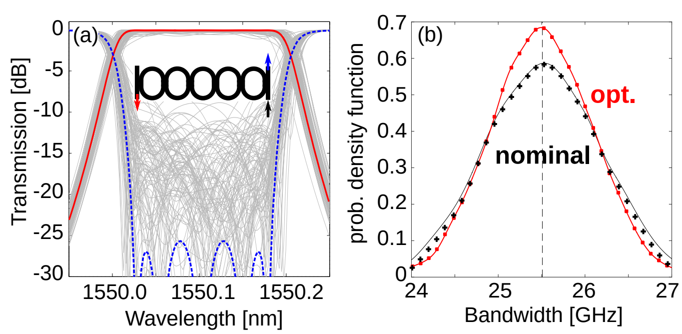

Fig. 1. (a) Transfer functions of the drop port (red bold solid line) and through port (blue bold dashed line) of the filter nominal design. Gray thin lines plot 100 Monte Carlo simulations when fabrication variations exist on the effective index of each ring and gap width of each directional coupler. (b) Probability density function of the 3-dB bandwidth of the unoptimized nominal design of the filter (black line and crosses) and optimized design (red line and dots).

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techniques to obtain optimized designs with increased robustness to fabrication tolerances. A sensitivity analysis would help discover the parameters that have the larger impact on a given quantity of interest [4]. The technique described in [5] was applied with the goal to optimize the design value of the coupler gaps in order to minimize the fluctuations of the bandwidth under the described process variations, that is minimize the mean-square-error (MSE) of the bandwidth with respect to the designed value 25.6 GHz. The design variables (gaps) were forced to be comprised between 0.29 µm and 0.31 µm. We hence exploited the sparsity structure of the problem to construct a sparse combined generalized polynomial chaos model, which is then used to analyse the statistics of the bandwidth and perform robust design optimization. The optimized gaps resulted to be [0.29, 0.31, 0.2947, 0.2931, 0.31, 0.29] µm. Figure 1(b) shows with red line the pdf of the 3-dB bandwidth of the optimized design. As can be seen, the optimized circuit has a bandwidth that is less dispersed around the central value, with a reduction of 18 % in the MSE compared to the unoptimized nominal design, demonstrating that the circuit bandwidth is less affected by the considered fabrication uncertainties. The optimized solution allows also increasing the fabrication yield of the circuit up to 8 %.

III. Tune after fabrication: locking strategies

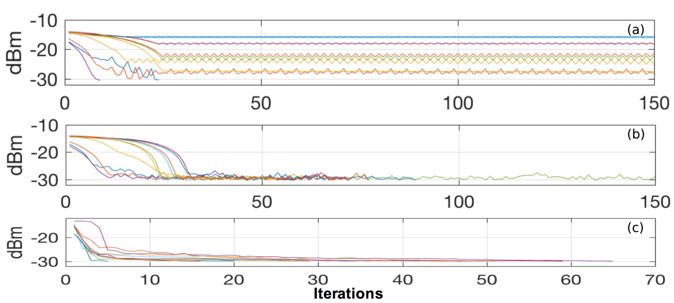

Fig. 2. Value of the error function at different iteration steps of the locking algorithm applied to the ring resonator filter, (a) with independent sequential stepping of the rings, (b) with transformed coordinate method and (c) exploiting an adaptive scheme in the transformed coordinate method.

The problem of circuit control can be particularly challenging in high-index-contrast photonic platforms, due to the large sensitivity of the optical parameters of the devices even to tiny geometrical variations occurring during fabrication, mainly inducing random phase errors. This is particularly true for high-order coupled microring resonator filters. The use of these devices cannot be addressed without proper tuning and locking technics that can be significantly more complex than the approaches required for the control of a single ring, due to the larger number of degrees of freedom, the existence of non-negligible coupling between rings and the risk of trapping in sub-optimal local solutions. Common tuning strategies presented in literature explore iterative approaches to overcome this problem [6], [7]. These sequential tuning algorithms are based on sweeping the resonance of each microring individually (generally through thermo-optic actuators) until reaching an optimal working point for the entire filter. On the other hand, the use of thermo-optic actuators leads almost unavoidably to the problem of handling thermal cross-talk that causes unwanted phase changes in adjacent rings close to the one under control. Thermal cross-talk may hence make sequential methods inefficient in tuning the working point of a filter. We propose here a novel method (transformed coordinate method) for the tuning and locking of a coupled microring resonator filter. With this technique, the thermal phase controller of all the rings that realizes the filter are tuned simultaneously at each iteration of the algorithm to minimize the target error function. The effectiveness of this technique is demonstrated by experimentally tuning a 3rd order microring-based filter fabricated in SiON platform starting from ten different randomly perturbed conditions. Adopting conventional sequential tuning of the resonators, the convergence is not always obtained, as shown in Fig. 2(a). The transformed coordinate method, on the other hand, converged in all the ten cases [Fig. 2(b)], demonstrating its effectiveness. Convergence could be accelerated by adopting an adaptive scheme during the process, as shown in Fig. 2(c) that presents a faster convergence in terms of iterations to more accurate results.

IV. Conclusion

In conclusion, we have shown that complex photonic circuits largely benefit from the use of advance techniques both during the design phase and for the actual operation. Optimization technique can improve the yield of a fabrication process, increasing the robustness of a design to uncertainties. Advanced control strategies such as the proposed transformed coordinate method allows to effectively exploit complex design also in presence of unavoidable tolerances. This toolbox is strategic for a fully exploitation of the capabilities of photonic circuits.

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