Yield Prediction for Coupled-Resonator Optical Waveguides Using Variation-Aware Compact Models

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Abstract: We present a model for coupled-resonator optical waveguide (CROW). A variation-aware Compact model provides CROW component S-parameters under varying spatial design perturbations, allowing efficient Monte-Carlo simulations and yield prediction. © 2019 The Author(s)
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1. Introduction

Significant computing and communication system performance gains can be achieved by transferring information using optical rather than electrical signals [1]. Often, on-chip optical buffers are needed that delay the optical signals. Coupled resonator optical waveguides (CROWs), where a number of ring waveguides are chained together as in Fig. 1(a), serve as a slow wave structure that can be used for buffering and storing data [1-3]. However, CROWs are challenged by the spatial variations within die or across the wafer, as CROWs are large structures extending hundreds of microns to millimeters in length, depending on the number of constituent rings. Geometric variations can change the passband or more importantly, may cause the CROW to fail if the spatial variations cause the resonances of the coupled rings to lose their alignment. We develop a method and variation-aware compact models that can be used to simulate and predict the CROW behavior against spatially correlated process variations in length and width.

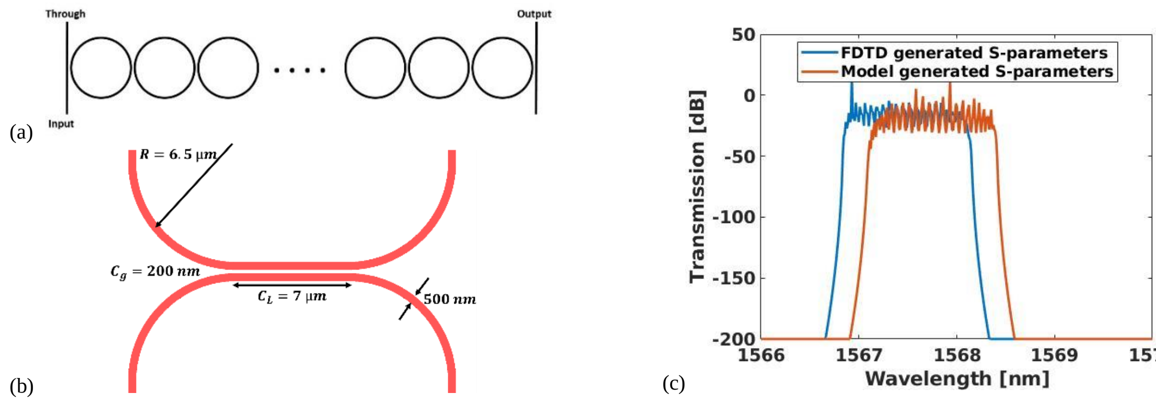

Fig. 1. (a) Schematic of CROWs, (b) geometry of half ring used during CROW model development, with Si waveguide nominal width W=500 nm, thickness T=220 nm, coupling length (C_L)=7 μm and coupling gap(C_g)=200 nm, (c) transmission simulation using half-ring variation-aware compact model vs. using direct half-ring FDTD-based S-parameter model, for 28 ring CROW with W=504 nm and T=220 nm.

2. S-Parameter Model

Generally, because a CROW consists of a large number of coupled rings it is infeasible to simulate the whole structure directly using a device level simulator (FDTD). Instead its simulation is based on generating the scattering parameters (S-parameters) for a constituent device component such as the half ring in Fig. 1(b) with a finite difference time domain (FDTD) simulator, and then simulating the whole CROW with a photonic circuit simulator by connecting half rings together. The S-parameters generated in the FDTD simulator are specific for a certain half ring waveguide design (i.e., fixed thickness and width). So, varying the ring design requires re-generating the S-parameters which is computationally expensive if a large number of half-ring variants must be considered. This highlights the need for a variation-aware compact model for device components, especially considering the fact that large numbers of these simulations are needed for Monte-Carlo statistical simulations or during design optimization.

We develop a parametrized variation-aware compact model for the CROW constituent device – a half ring with nominal design parameters – as shown in Fig. 1(b). This model provides the S-parameters for the half ring under varying thickness or width, with acceptable accuracy and much less computational cost than repeated FDTD simulations. The model is developed to predict both magnitude and phase of S-parameters using polynomial regression, where a 3rd order polynomial models the S-parameter magnitude variations with width and thickness. The magnitude model has an $R^2$of 0.969 and 0.993 for width and thickness, respectively. A 5th order polynomial models the S-parameters phase variations with an R^2 of 0.99 for both width and thickness variations.

The S-parameters generated from the model can then be used in a photonic circuit simulator to simulate CROWs of any length. Fig. 1(c) shows a comparison between the simulated performance of a 28 ring CROW using S-parameters generated directly from FDTD simulation and S-parameters generated using the developed variation-aware compact model. As seen in Fig. 1(c), both result in very similar passband transmissions (our most important yield parameter) and bandwidth, though with an offset in passband center wavelength. However, the compact model generates the S-parameters in few seconds, while the FDTD-based S-parameter models require ~90 minutes to generate. All optical simulations are done using Lumerical FDTD [4] and INTERCONNECT [5].

3. Model Applications

This parametrized compact models can be used to facilitate and speed up design optimization, Monte-Carlo simulations and yield prediction. A Monte-Carlo simulation case is examined when all of the rings in the CROW experience the same variation. The compact model is used to construct the S-parameters for the circuit level simulation given random sample values for width and thickness. Fig. 2(a) shows the variation in resonance wavelength using the compact model to simulate 100 different CROWs consisting of 28 rings, each with a randomly sampled thickness (assuming normally distributed thickness, 220 nm nominal, standard deviation 1 nm).

Another application for these models is predicting the yield when the rings within the CROW experience spatially correlated variations in waveguide width or thickness as in Fig. 2(b). For yield prediction, we run 100 different instantiations of spatially correlated width and thickness process maps. According to each, we generate S-parameters for every ring based on its local thickness and width values within the process spatial map. We consider working CROWs to be those where the pass band transmission is more than -20 dB. Yield simulations in response to width and thickness variations are shown Fig. 3, as a function of spatial correlation length (L_c) and amplitude (σ).

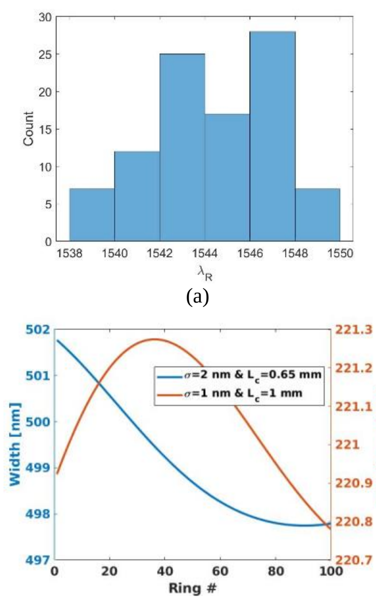

Fig. 2. (a) Resonance wavelength variation with thickness variation with a standard deviation 1nm, (b) spatially correlated variation map for a single instantiation of a CROW consisting of 100 rings.

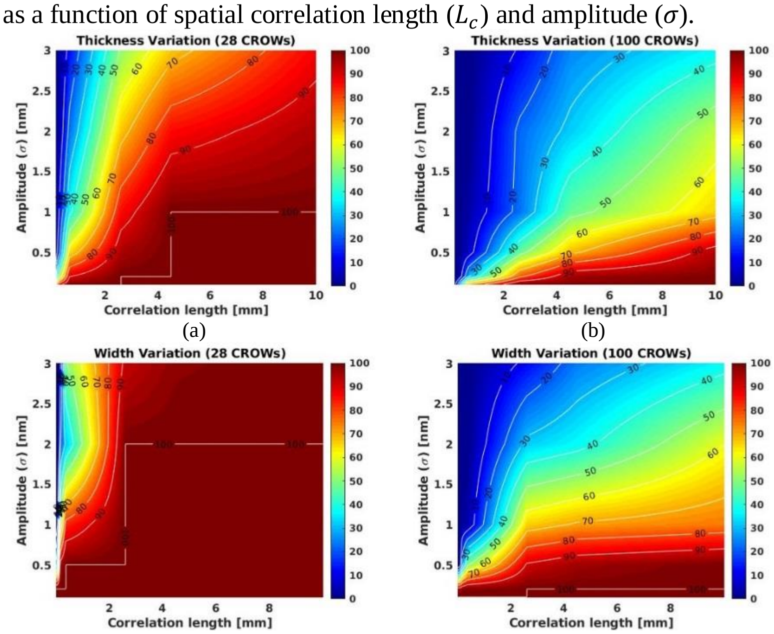

Fig. 3. Yield (%) vs. spatial length correlation and amplitude of (a) thickness for 28 ring CROWs, (b) thickness for 100 ring CROWs, (c) width for 28 ring CROWs, and (d) width for 100 ring CROWs. Low yield results with short correlation length and large amplitude vars.

4. Conclusions

The compact model demonstrated here can serve as a building block for a variation-aware process design kit (PDK) for photonics. Such models enable silicon photonic designers to run Monte-Carlo simulations, predict performance, and optimize yield of their silicon photonic devices and circuits given the variance specifications of a specific foundry.
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5. References

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