Efficient Design of Photonic Integrated Circuits (PICs) by Combining Device- and Circuit- level Simulation Tools

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ABSTRACT

This work addresses a versatile modeling of complex photonic integrated circuits (PICs). We introduce a co-simulation solution for combining the efficient modeling capabilities of a circuit-level simulator, based on analytical models of PIC sub-elements and frequency-dependent scattering matrix (S-matrix) description, and an accurate electromagnetic field simulator that implements the finite element method (FEM) for solving photonic structures with complicated geometries.

This is exemplified with the model of a coupled-resonator induced transparency (CRIT), where resonator elements are first modeled in the field simulator. Afterwards, the whole structure is created at a circuit level and statistical analysis of tolerances is investigated.

1. INTRODUCTION

Photonic Design Automation (PDA) is becoming one of the main drivers in the development of photonic integrated circuits (PICs). The simulation of a photonic circuit can be very complex because of the large diversity of photonic components, the broad frequency ranges of optical signals involved and due to the presence of very different characteristic lengths (and thus time scales) in the simulated circuit. To properly handle such diversities, modern photonic circuit simulators are based on the segmentation of the modeled PIC into building blocks. Each PIC element is coupled to other PIC elements via guided modes of channel optical waveguides. This allows to separate circuit-level modeling from device-level modeling and facilitates that different PIC elements in the same circuit are modeled by different methods.

In previous works we have addressed the modeling of fully passive PICs, based on the description of PIC elements in terms of frequency-dependent scattering-matrices [1]. Lately, we presented a new method for efficient modeling of hybrid large-scale PICs that aids pure time-domain simulations, so called, time-and-frequency domain modeling (TFDM) [2]. Although a circuit-level approach covers a large field of application designs, traditional photonic simulation techniques based on solving the Maxwell equations are complement for modeling specific PIC elements with higher level of geometrical details.

In this contribution we present a solution for co-simulation within a circuit-level simulator and a full 2D/3D simulator that implements frequency-domain finite-element method (FEM) for solving photonic devices with any geometry. In this procedure, the layout of the ring resonator, wire, and slab wires is designed in the FEM-based simulator and an accurate calculation of waveguide parameters is performed. The results are shared with the circuit-level simulator, which is used to design and optimize the device topology.

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2. SIMULATION ENVIRONMENT

2.1 Design Flow

The ultimate goal of a design is to be fabricated by a foundry. Nowadays, the technology used at foundries is still far from being perfect – there are sufficiently strong variations of waveguide height, width and roughness which should be minimized and then compensated in designed circuits by using heaters, for instance, or by fabricating several samples of the circuit in the same wafer. This fact emphasizes how important it is to start a design from the circuit level and evaluate different solutions, analyze tolerances of fabrication processes, or calculate the power budget.

In such a design cycle, from top to bottom, i.e., from application design to fabrication design, circuit simulation tools such as VPIcomponentMaker Photonic Circuits [3] or others [4] are placed at the top level. Important design aspects to be solved at circuit level are:

- Choice of technology (InP, Silicon, ...): The total insertion loss, the minimum radius and width of the waveguides, as well as the minimum waveguide separation depend directly on the technology.
- Investigation of alternative designs: The same application might be solved with different implementations. For instance, WDM filtering can be performed with AWG elements, cascaded or parallel ring-resonator structures. Power splitting can be accomplished using coupled waveguides but also using MMI structures.
- Sensitivity analysis of geometrical imperfections and thermal effects: Paths of different length might introduce amplitude and phase imbalances. A rise in temperature might imply differences at the resonance frequencies.

At the device level, Maxwell's equations inside the structure are solved, following the exact geometry, and accounting for the impact of characteristics as small as roughness and curvatures, in two- or three-dimensional representations. Further, an accurate calculation of the propagation constant can be obtained. The propagation constant, or the related effective index, are one of the main input parameters for the circuit simulator. In the design process there might be several iterations between circuit- and device-level simulators before proceeding with the design on the technology level.

On the technology level, the layout and cross section of the circuit are created. Using a layout design tool, the locations of optical and electrical ports are fixed and the space is optimized. In this step, final foundry specific design rule checks are carried out as well.

The output of this design circle could be a file containing planar geometric shapes and layer information for the specific foundry. Completing the cycle, once the device is fabricated, characterization measurements can be used in the circuit design for specifying the range of tolerances associated to that technology or for developing new analytical models.

As a summary, in a top-down design flow, the circuit-level simulator is used for fast prototyping of the device by analytical expressions or pre-calculated transfer functions. Alternatively, it may call the device-level simulator from individual sub-elements in the circuit, which require a deeper level of analysis, or, when the design reached a mature stage, call a mask-layout software and close the design process.

2.2 Circuit-level simulations with VPIcomponentMaker Photonic Circuits

With the circuit-level simulation approach implemented in VPIcomponentMaker Photonic Circuits, a photonic IC is composed out of several active and/or passive sub-elements, also named PIC elements (Fig. 1, left). Each PIC element represents a functional building block with several input and/or output ports. Each port is represented by optical channel waveguides that support two orthogonally polarized fundamental guided modes (TE-/TM–like), described by Ex/Ey signal components. Ports are bidirectional, so that back reflections and coupling of counter-propagating waves can be accounted for (Fig. 1, right). Thus, each PIC element can be seen as a black-box producing outgoing guided modes of the device ports from the corresponding incoming modes.

PIC elements in the same circuit can be modeled by different methods and with different simulation accuracy. Passive elements are commonly described in terms of frequency defined S-matrices, while active parts are modeled in the time domain by means of the transmission-line model (TLM). At the same time, S-matrices can be either calculated from built-in analytical models or loaded from a file. Passive PICs, consisting of linear PIC elements only, can be efficiently modeled in the frequency domain. However, the presence of non-passive PIC elements, such as lasers, SOAs, and modulators requires a time-domain simulation solution. In that case, the hybrid Time-and-Frequency-Domain Modeling (TFDM) solution is employed [1].

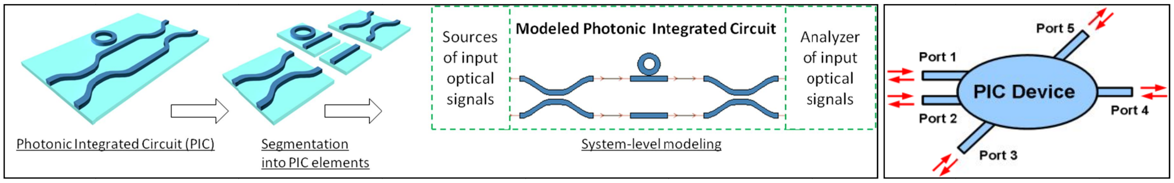

Figure 1. PIC simulation based on segmentation into fundamental sub-elements (left) and representation of a 5-port PIC device (right).

Analytical models of S-matrices are based on established theoretical models. Theoretical models are formulated in terms of the TE/TM fundamental guided modes of the waveguides embedded forming the element. Either the propagation constant or the frequency-dependent effective mode index is necessary for the calculation of the guided modes. Following the Bloch-Floquet theorem, the electric field distribution for the guided modes can be expressed as

$$\vec{E}_v(\vec{r},f) = e^{-j\beta_v(f)z}\vec{F}_v(x,y,f)$$

where $\vec{r} = (x,y,z)$ describes the radius-vector expressed in cartesian coordinates with the z-axis being directed along the modeled waveguide and the (x,y)-plane lying along the waveguide cross-section area, $\beta_v(f)$ defines the propagation constant of the guided mode v at the given frequency f, and $\vec{F}_v(x,y,f)$ defines the field profile of the guided mode within the waveguide cross-section area.

The propagation constant $\beta_v(f)$ defines the phase and group delay accumulated by the optical signal of the mode. In practice, the model operates with the related variables effective mode index and group mode index, which define the phase and group delay of the signal. Close to a reference frequency, the propagation constant can be restored by using Taylor series expansion as:

$$\beta_v(f) \approx \frac{2\pi f_0}{c} n_{eff,v}(f_0) + \frac{2\pi}{c} n_{gr,v}(f_0)(f-f_0) - \frac{c^3 D_v(f_0)}{4\pi f_0^2}(f-f_0)^2$$

It is clear that the accuracy of the modeled circuit depends on the accuracy of the approximations of the effective index, group index and dispersion (n_{eff}, n_{gr}, D_v) of the different PIC elements.

2.3 Device-level simulation with JCMsuite

JCMsuite [5] is a software package that allows simulating the propagation of electromagnetic fields with an exceptionally high accuracy. It implements the finite element method (FEM) which is very well suited for rigorous simulation of complex photonic devices and structures. The method is based on high order vectorial elements, adaptive unstructured grids, and on rigorous, self-adaptive treatment of transparent boundaries. Together with convergence monitors and error estimation techniques this ensures high accuracy of simulation results at high speed and moderate problem sizes. JCMsuite handles 1D, 2D, cylinder symmetrical 3D, and arbitrary 3D geometries, materials with complex refractive indices and anisotropic material constants [6]. The capability of embedded scripting makes it very convenient to set up parameterized projects and complicated geometries and to perform parameter scans with nested loops over project parameters like wavelength, incident angle or geometrical quantities. Embedded scripting is supported for Matlab, Octave, and Python. Besides controlling the solver, the simulation results can be imported into the corresponding environment and can then be further processed. Embedded scripting is also used in the presented cosimulation approach to establish a convenient interface between VPIcomponentMaker Photonic Circuits and JCMsuite.

Because of JCMsuite's advantages when simulating photonic devices with complex geometries, it represents a very good supplement to the photonic circuit-level simulator VPIcomponentMaker Photonic Circuits.

3. COSIMULATION DESIGN PROCESS

3.1 Considerations

The usage of the frequency-domain FEM approach implies several limitations in the designs. Foremost, it can be used for modeling only linear passive materials. An extension of this approach to nonlinear or active materials is not trivial and it would be better just to change the simulation approach to time-domain FEM simulations. Another difficult problem for FEM is the analysis of device responses to short pulses or rapidly modulated signals. Beside those matters, it can be used for accurate and efficient calculation of all eigenmodes of photonic devices, such as guided modes of waveguides with arbitrary geometries and/or resonance modes of micro-rings and micro-disks. Additionally, any dispersive materials (including metals) can be modeled accurately and efficiently.

3.2 Design procedure

Step 1: Layout design of wire and slab waveguides in the device-level simulator

After defining the exact geometry of the device, waveguide dispersion, effective and group indices are calculated accurately in 2D/3D simulations. In the first step it is also possible to estimate waveguide loss due to energy leakage to the substrate when the guided mode is not guided completely, but radiating as well. Additionally, waveguide loss, index change and mode coupling due to waveguide bending are estimated. These parameters can be parameterized with sufficient accuracy as functions of the bending radius with few constants that should be calculated by solving Maxwell's equations. Furthermore, the effect of backscattering inside straight/bent waveguide due to sidewall roughness is analyzed. This effect represents one of the main limiting factors for applications of high-Q micro-rings.

Step 2. Export model parameters and apply in the circuit-level simulator

The model parameters found during Step 1 are substituted into the circuit-level simulator, which is used to design and preliminary optimize the topology of the photonic integrated circuit. At this stage, it can be set to operate with natively supported analytical models and get estimates of the required structural parameters. For instance, when modeling a ring resonator, the desired resonance parameters (resonant frequency, free spectral range, Q-factor) and the above-calculated waveguide parameters (effective index, group index, dispersion, attenuation) are employed for obtaining estimates of the structural parameters (ring diameter, waveguide length, coupling coefficient between straight and ring waveguides). Automated sweeps and script-assisted optimization routines allow investigation of many parameter variations in very short time, and thus, help the designer to find optimum topology settings.

Step 3. Optimization of PIC sub-elements in the device-level simulator

After designing the integrated device on the circuit level, the user would need to come back to the device-level simulator and perform the final optimization of important PIC elements (e.g., their layouts). After completion, the user shall be able to save the final S-matrices of the optimized components into files for further system performance analysis of the PIC.

Step 4. Verification of PIC performance using the circuit-level simulator

The S-matrices calculated in Step 3 are loaded by the circuit-level simulator and used for verifying the final performance of the integrated device. The optimized sub-elements can also be used as initial building blocks for designing other composite devices at the circuit level.

4. APPLICATION EXAMPLE: COUPLED-RESONATOR-INDUCED TRANSPARENCY (CRIT)

4.1 Ring-Coupler Design

To illustrate the cosimulation design process described above, we consider a PIC formed by two coupled silicon ring resonators with 10um diameter (Fig. 2) connected by two straight waveguides. This structure exhibits the effect of coupled-resonator-induced transparency (CRIT) – an all-optical analogue to electromagnetically induced transparency (EIT) [7, 8]. CRIT devices provide an efficient tunable transparency on the optical chip, and are considered as crucial step towards the development of integrated all-optical chips [9].

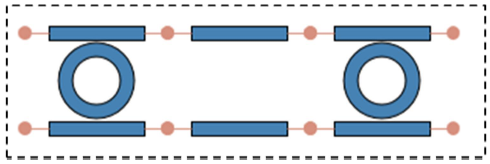

Figure 2. Schematic of a CRIT in VPIcomponentMaker Photonic Circuits

Each ring coupler is composed of two bus waveguides coupled to a ring. The ring coupler is first designed using the device-level simulator (Fig. 3). The S-matrices of its transfer functions at the four ports and the frequency-dependent effective index are calculated. Then, the calculated data is used in the circuit-level simulator. Fig. 4 displays the response at one of the ports for the analytical model, which uses as inputs effective and group indices, dispersion and geometrical 1D description (radius, bus length and bus-ring separation), and for the measured model, which uses the pre-calculated S-matrices. Both responses are equivalent close to the resonance frequency. Therefore, the extracted parameters can be used to feed the ring couplers in the CRIT structure.

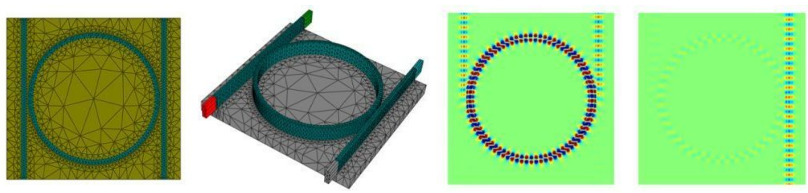

Figure 3. Design of the ring resonator in JCMsuite. From left to right: 2D, 3D geometries, field intensity at a resonance frequency, field intensity at a non-resonance frequency

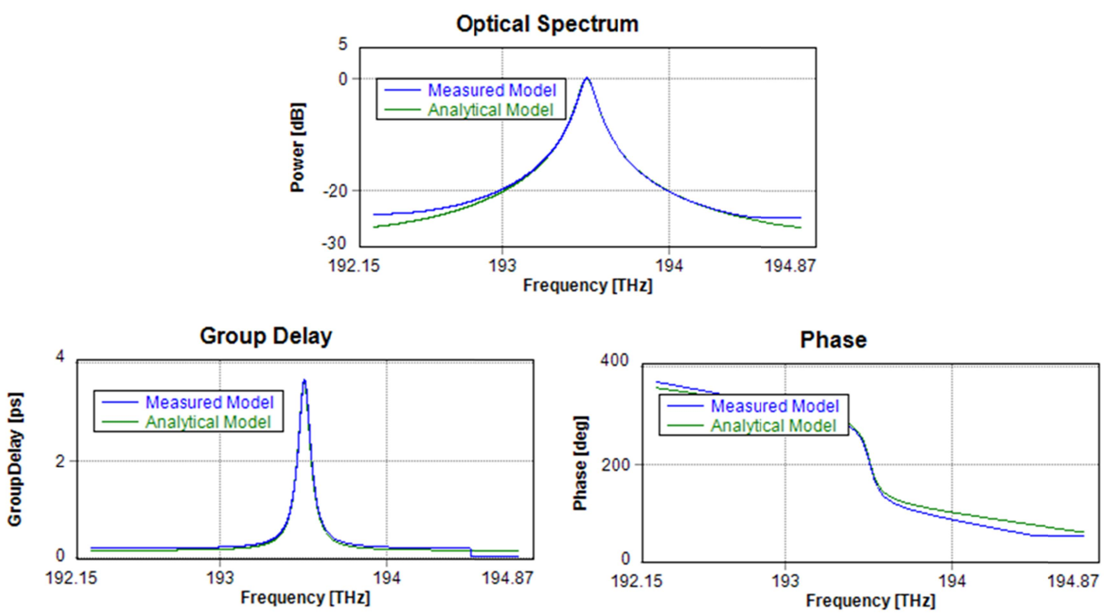

Figure 4. Spectrum, group delay and phase responses at the output of a single ring coupler for measured and analytical models

The performance of the whole circuit and the optimization of the device topology can be efficiently carried out in the circuit-level simulation. Fig. 5 represents exemplary responses at the through and drop ports of the CRIT. As expected, a narrow transparency peak at the center of a broader resonant reflection line appears at the through port.

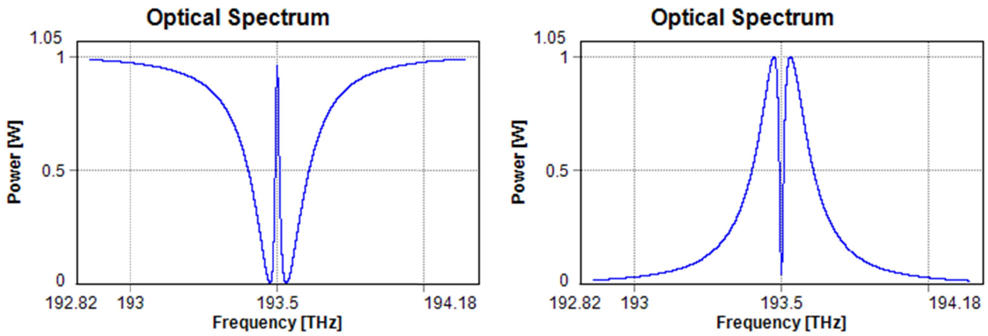

Figure 5. Response of the CRIT at the trough (left) and drop ports (right)

By modifying the attenuation inside the ring, one observes that the intensity of the narrow peak intensity depends on the ring waveguide attenuation (Fig. 6). The diameter of one of the rings is slightly detuned to analyze the dependency in the broadening of the central peak (Fig. 7). The effect of slight separation between the two rings can be investigated as well. Fig. 8 shows that a deviation in the waveguides connecting the rings has a strong impact on the functionality of the device (Fig 8).

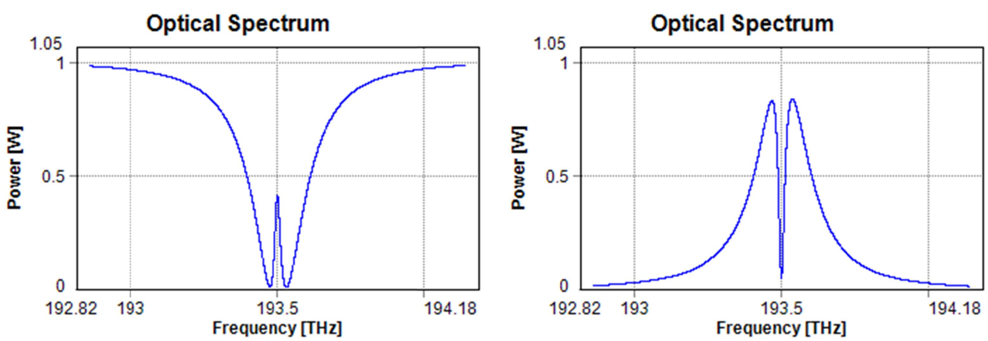

Figure 6. Response of the CRIT at the trough (left) and drop ports (right). Attenuation of the ring 3000dB/m

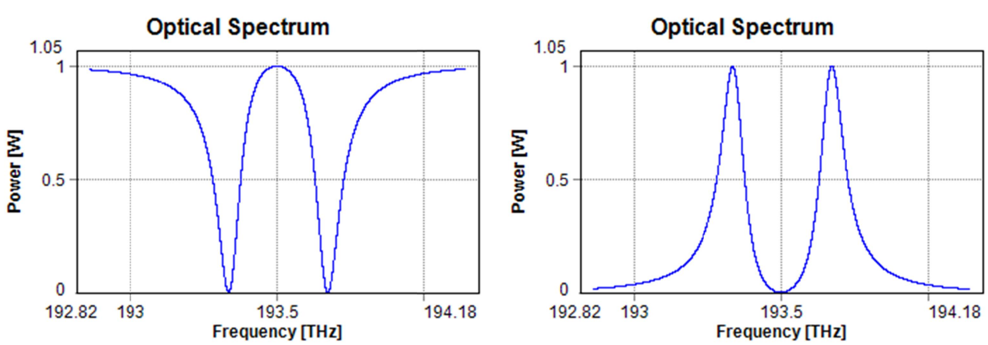

Figure 7. Response of the CRIT at the trough (left) and drop ports (right). Ring length detuning of 0.6nm

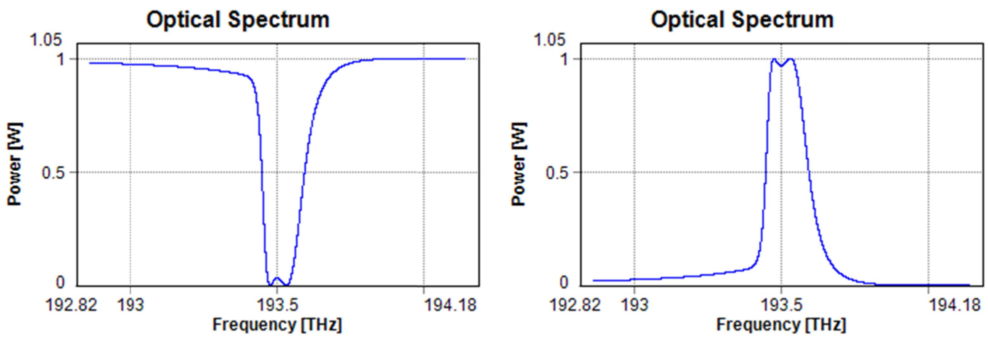

Figure 8. Response of the CRIT at the trough (left) and drop ports (right).Length deviation 0.1µm.

5. SUMMARY

With this work, we have presented a cosimulation framework for photonic integrated circuits that combines professional device- and circuit-level simulation tools, namely VPIcomponentMaker Photonic Circuits and JCMsuite. We have motivated that the design process of PICs should comprise several steps with clear design functions. It is crucial to execute circuit-level simulations first to perform optimization and tolerance evaluation of the whole integrated circuit. In order to ensure accuracy and reliable results, models of important building blocks of the assembled PIC should be first specified using more detailed descriptions as 2D or 3D geometries at device-level. We demonstrated that the frequency-domain FEM approach used in JCMsuite complements the usage of VPIcomponentMaker Photonic Circuits in the design flow of photonic integrated circuits.

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