Hybrid Time-and-Frequency-Domain Approach for Modeling Photonic Integrated Circuits

Sergei Mingaleev and Eugene Sokolov
VPI Development Center, Minsk, Belarus
Email: sergei.mingaleev@vpisystems.com

Cristina Arellano, Igor Koltchanov and André Richter
VPIsystems, Berlin, Germany

***Abstract*—Modern simulators of photonic integrated circuits (PICs) employ either frequency-domain or time-domain approaches for system-level modeling of PICs. We critically examine limitations of both approaches that obstruct their usage for simulations of large-scale PICs, and suggest an efficient hybrid alternative. Within this new approach clusters of connected linear PIC elements are modeled in frequency domain, while interconnections between such clusters and non-passive PIC elements are modeled in time domain.**

I. Introduction

During the last decade, photonic integrated circuits (PICs) exhibit an exponential increase in complexity, resembling Moore's law in micro-electronics [1]. Specifically, the number of photonic components integrated on a single chip exceeded three hundreds in 2010, and is expected to double every 2.5 years [2]. Note that the current level of integration has been reached by micro-electronics by 1967 — during the infancy of the first electronic circuit analysis programs. Remarkably, now we recapture those times once again, living in the beginnings of commercially available photonic circuit simulators [3–5].

In contrast to traditional photonic simulators (implementing methods like FDTD or BPM for solving Maxwell's equations *for the complete structure*), photonic circuit simulators are based on segmentation of the modeled PIC into building blocks ("PIC elements"), as illustrated in Fig. 1. Each PIC element is a photonic device that is coupled to other PIC elements only via guided modes of channel optical waveguides — the so-called "ports". Because of this, each PIC element can be considered as "black box" that produces outgoing waves carried by guided modes of the device ports from the corresponding incoming waves. This allows to separate system-level modeling of PICs from device-level modeling of PIC elements. The latter can be performed either using traditional photonic simulators, or employing analytical and behavioral models of PIC elements. Importantly, different PIC elements in the same circuit can be modeled by different methods, thus allowing initial rapid prototyping of the circuit and subsequent gradual improving of the simulation accuracy.

The system-level modeling of PICs is currently performed using one of two approaches. Passive PICs, consisting of linear PIC elements only, can be efficiently modeled in frequency domain [3,5]. However, the presence of non-passive PIC elements inside the modeled PIC, such as lasers, SOAs, modulators and, generally, any nonlinear or dynamically tunable devices makes time-domain simulation necessary. Importantly, in this case all the linear PIC elements are also modeled in time domain, employing digital FIR filters designed on the basis of their frequency-dependent scattering matrices [4,5].

In this contribution, we show that neither pure time-domain nor pure frequency-domain approaches can be used for system-level modeling of forthcoming large-scale PICs with hundreds (or more) of passive elements and relatively few embedded non-passive elements. As one of the most promising solutions to this problem, we suggest the usage of a hybrid Time-and-Frequency-Domain Modeling (TFDM) approach.

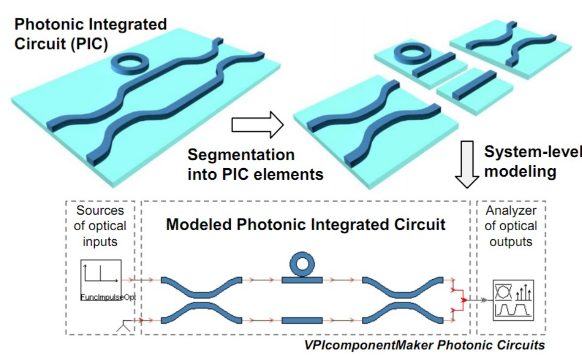

Fig. 1. Illustration of the modeling philosophy exploited in all modern photonic circuit simulators (adapted from [5]).

II. Frequency-domain approach to passive circuits

Fully passive PICs that consist of linear PIC elements only pertain to linear time-invariant systems. Their analysis can be best performed, after Fourier transform, in frequency domain. In this case, each PIC element is completely described by a frequency-dependent scattering matrix (S-matrix) that relates amplitudes of incoming and outgoing guided modes at all device ports [6]. The advantage of this approach is that the system response can be calculated for each signal frequency independently, thus allowing efficient parallelization of simulations and high accuracy for even narrow-band input signals (what additionally significantly reduces memory and computation time requirements). Moreover, the properties of the entire circuit can be described by recursive combinations of the S-matrices of individual PIC elements into a total S-matrix [7]. Altogether, this approach allows an extremely fast and highly precise analysis of passive PICs (see for instance

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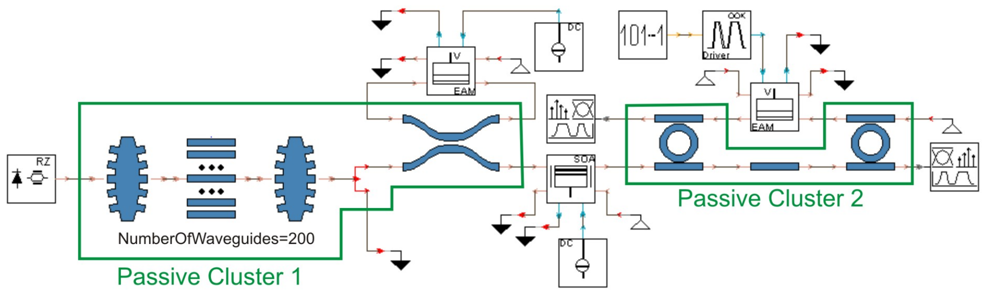

Fig. 2. Example of PIC with marked clusters of interconnected passive PIC elements — each cluster is characterized by a single combined S-matrix.

[8]). Regrettably, all these advantages fade away as soon as the modeled photonic circuit includes non-passive PIC elements.

III. Time-domain approach to active circuits

Currently, modeling of non-passive PICs is commonly performed in time domain. In this case, all the PIC elements that comprise such PICs are modeled in time domain — *including each of the linear PIC elements*, even if the modeled PIC contains only a single non-passive PIC element. Theoretically, the time-domain modeling of linear PIC elements is equivalent to their frequency-domain modeling. The only difference is that the multiplication of the device S-matrix with the amplitudes of the input signals in frequency domain should be replaced by the convolution of the device impulse response matrix with the amplitudes of the input signals in time domain. However, in practice such a translation is inevitably inaccurate - both, in calculating the convolution (due to time discretization) and in calculating the impulse response matrix (due to the non-acquaintance of the device S-matrix outside a prerequisite frequency range). Also, time-domain modeling is more sophisticated as it requires the *linear* convolution and a *causal* impulse response, while frequency-domain modeling is mathematically equivalent to the circular convolution and can support even non-causal impulse responses of idealized or approximate component models. Commonly, time-domain modeling of linear PIC elements is implemented using digital FIR filters designed on the basis of the device S-matrices.

Although the accuracy provided by FIR filters substantially depends on the quality of the employed FIR design methods (and thus their elaboration constitutes one of the most important modeling tasks), it inherently degrades near the edges of the simulated signal bands, even for the best designed FIR filters. In practice, such inaccuracy is not very important when the longest lightpaths in the modeled PIC pass through only several linear PIC elements. However, due to multiplicative effects, the net bandwidth where simulation results remain accurate rapidly decreases as the number of PIC elements in the simulated PIC increases.

This problem becomes even harder in the presence of short-length PIC elements (for example, small microrings or waveguides connecting neighboring devices) since their short impulse responses require smaller time steps for accurate modeling and increased computation effort. Any inaccuracies are further magnified by feedback loops, which are always present in large-scale PICs. For keeping a prerequisite simulation bandwidth all this enforces to use smaller and smaller time steps as the complexity of the modeled PIC grows, thus precluding scalability of the described time-domain approach.

Summarizing, the time-domain approach is not scalable for system-level modeling of PICs and becomes impractical as the number of PIC elements exceeds several tens.

IV. Hybrid time-and-frequency-domain modeling approach to large-scale circuits

To overcome aforementioned limitations we suggest using hybrid TFDM. Within this approach, the topology of the modeled PIC is first analyzed, and clusters of interconnected passive PIC elements are identified, as illustrated in Fig. 2. For each of these clusters, all S-matrices of their individual PIC elements are recursively combined into a single S-matrix that describes the properties of a cluster as a whole. Finally, FIR filters are designed for each of these clusters, and the usual time-domain approach is employed for modeling properties of the whole PIC including its non-passive components. In practice, the number of such clusters will be comparable with the number of non-passive PIC elements — which is usually many times smaller than the number of passive elements.

We will present our implementation of the TFDM approach and discuss its scalability and performance. We show that TFDM greatly improves accuracy, memory requirements and simulation speed in comparison with the time-domain approach for system-level PICs simulations.

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