Towards system-level modeling of large-scale active photonic integrated circuits

Recent advances and remaining challenges

Sergei Mingaleev and Eugene Sokolov
VPI Development Center, Chapaeva str. 5,
220034 Minsk, Belarus
Email: sergei.mingaleev@vpisystems.com

Cristina Arellano, Igor Koltchanov, and André Richter
VPIsystems, Carnotstr. 6,
10587 Berlin, Germany

***Abstract* — Recent advances in the fabrication of large-scale monolithic photonic integrated circuits (PICs) which embed different types of active photonic components require the development of appropriate simulation tools. Specifically, such tools should be fast and accurate in modeling both, passive and active photonic components. This enforces the usage of the system-level simulation approaches, which allow modeling of each individual photonic component with a specific (most suitable) numerical method. Another important requirement is that the simulation speed at the desired simulation accuracy should grow reasonably slowly with the total number of photonic components in the modeled PIC, even when this number is in the order of several thousands (practically achievable in few years). We show that this demand can be satisfied only when the system-level simulation tool mixes within a single simulation both, time-domain and frequency-domain approaches for the description of interconnections between different PIC components. We present our implementation of the suggested time-and-frequency-domain modeling (TFDM) approach in the framework of the simulation tool VPIcomponentMaker™ Photonic Circuits, and discuss its scalability to large-scale active PICs and remaining challenges.**

Large-Scale Photonic Circuits, Integrated Photonics, Time-and-Frequency-Domain Modeling, PIC, TFDM

During the last decade, photonic integrated circuits (PICs) exhibit an exponential increase in complexity, resembling Moore's law in micro-electronics. 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 [1]. Note that the current level of integration has been reached by micro-electronics by 1968 – during the infancy of the first electronic circuit analysis programs. Remarkably, now those times are recaptured once again, and we are living in the beginnings of commercially available photonic circuit simulators [2-4].

Importantly, the complexity of simulation techniques that should be used in photonic circuit simulators is greatly superior to those employed in electronic circuit simulators. This complexity is determined by several factors: large diversity of photonic components, broad frequency ranges of optical signals that require usage of advanced signal representations [5], presence of very different time scales, etc. To properly handle such a complexity, modern photonic circuit simulators [2-4] are based on segmentation of the modeled PIC into building blocks ("PIC elements"). 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 device-level modeling 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. Development of such a modeling looks sufficiently straightforward and thus shall not be discussed here. In contrast, system-level modeling of PICs presents a real challenge as soon as the modeled PIC includes active or dynamically tunable components, and the total number of PIC elements exceeds several tens.

More specifically, until recently only two approaches to the system-level modeling of PICs have been used. Passive PICs, consisting of linear PIC elements only, could be efficiently modeled in frequency domain [2,4]. 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. Employing the S-matrix assembly technique [4], one can calculate S-matrices of any compound passive devices. This approach allows fast and highly precise analysis of passive PICs, and scales nicely with the growing number of linear PIC elements. However, all these advantages fade away as soon as the modeled photonic circuit includes at least one non-passive PIC element.

Within the alternative time-domain modeling (TDM) approach [3,4], all the PIC elements that comprise the modeled PIC are modeled in time domain – including each of the linear PIC elements. Commonly, such a TDM of linear PIC elements is implemented using digital FIR filters designed on the basis of the device S-matrices. And although the accuracy provided

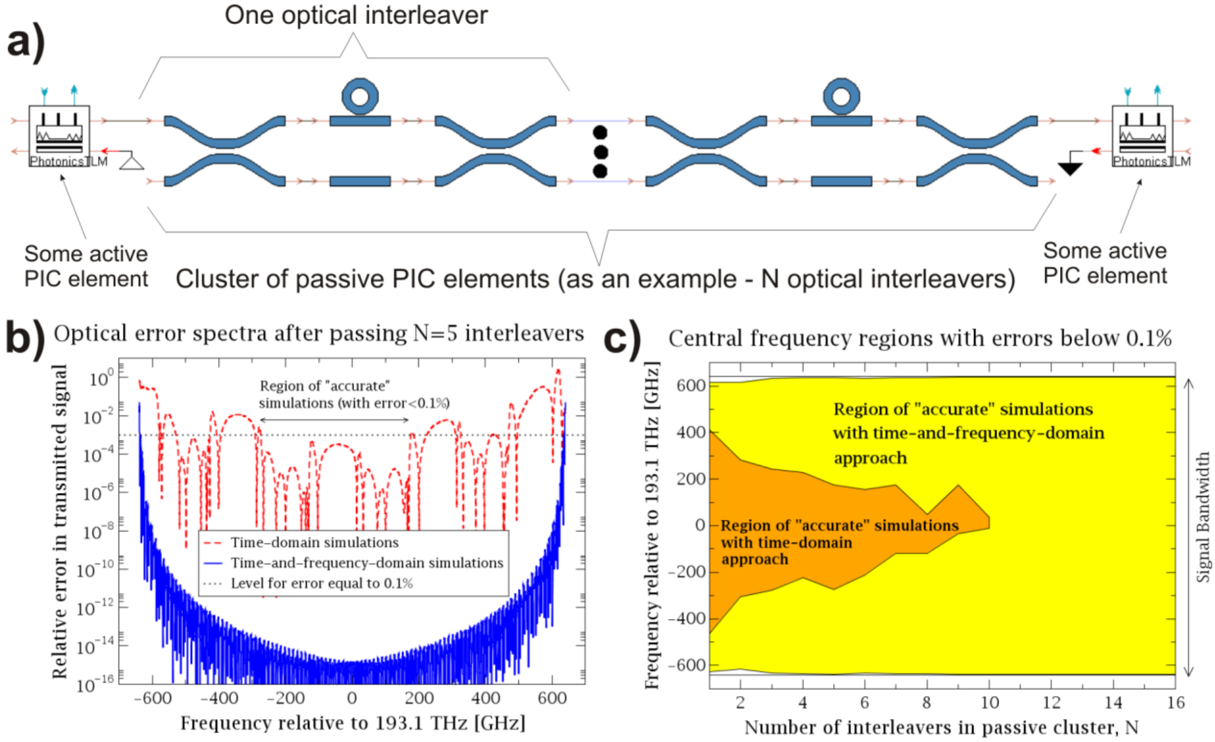

Figure 1. Comparison of the accuracy of pure time-domain modeling (TDM) and time-and-frequency-domain modeling (TFDM) approaches, on the example of modeling cascaded optical interleavers. Important: the time step and overall signal duration remained unchanged in all these simulations.

by FIR filters substantially depends on the quality of the employed FIR design methods, it inherently degrades near the edges of the simulated signal bands (see example in Fig. 1b), even for the best designed FIR filters. In practice, such inaccuracy is not very important for modeling PICs with only several linear PIC elements. However, as we illustrate in Fig. 1c, due to multiplicative effects, the net bandwidth where simulation results remain accurate rapidly decreases and then collapses as the number of PIC elements in the simulated PIC increases. This problem becomes a real toughie in the presence of short-length PIC elements (for example, small micro-rings) 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 TDM approach and making it impractical as the number of PIC elements exceeds several tens.

To overcome aforementioned limitations, we developed [4] a hybrid time-and-frequency-domain modeling (TFDM) technique. Within this approach, the topology of the modeled PIC is first analyzed, and clusters of interconnected passive PIC elements are identified. For each of these clusters, all S-matrices of their individual PIC elements are recursively assembled into a single S-matrix that describes the properties of the 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. As we illustrate in Fig. 1 on the example of cascaded optical interleavers surrounded by active PIC elements, such an approach allows to greatly improve accuracy of time-domain simulations keeping the same time step and signal duration. Importantly, the choice of time step in TFDM approach is determined by the needs of modeling active PIC elements, in contrast to TDM approach, where it was rather limited by inaccuracies in modeling passive PIC elements.

We will present further advances in our implementation of the TFDM approach in VPIcomponentMaker™ Photonic Circuits, and shall discuss its scalability and performance in application to large-scale active PICs.

REFERENCES

[1] M.K. Smit, "Moore's law in photonics", Plenary talk at ECIO, Cambridge, UK, 7-9 April 2010.

[2] A. Melloni et al., "Design Kits and Circuit Simulation in Integrated Optics", in Integrated Photonics Research, Silicon and Nanophotonics, paper JTuB24, July 2010. See also: ASPIC, http://www.aspicdesign.com

[3] D.F.G. Gallagher, "Modelling photonic integrated circuits using TDTW", in Optical Fiber Communication Conference, October 2008. See also: PICWave, http://www.photond.com/products/picwave.htm

[4] S.F. Mingaleev, E. Sokolov, C. Arellano, I. Koltchanov, and A. Richter, "Hybrid time-and-frequency-domain approach for modeling photonic integrated circuits", NUSOD, paper ThA4, September 2011; "Time-and-Frequency-Domain Modeling (TFDM) of hybrid photonic integrated circuits", SPIE Photonics West, paper 8265-19, January 2012; See also: VPIcomponentMaker™ Photonic Circuits, http://vpiphotonics.com/CMPhotonicCircuits.php

[5] A. Lowery et al., "Multiple signal representation simulation of photonic devices, systems and networks", IEEE J. Select. Topics Quantum Electron., vol. 6, pp. 282-296, 2000.