Towards an automated design framework for large-scale photonic integrated circuits

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ABSTRACT

We present our approach towards an automated design framework for integrated photonics and optoelectronics, based on the experience of developing VPIcomponentMaker Photonic Circuits. We show that design tasks imposed by large-scale integrated photonics require introducing new "functional" types of model parameters and extending the hierarchical design approach with advanced parameter scripting capabilities. We discuss the requirements imposed by the need for seamless integration between circuit-level and device-level simulators, and illustrate our approach for the combination of VPIcomponentMaker Photonic Circuits and VPImodeDesigner. We show that accurate and scalable circuit-level modeling of large-scale photonic integrated circuits requires combination of several frequency- and time-domain simulation techniques (scattering-matrix assembly, transmission-line models, FIR and IIR digital filters, etc) within the same circuit simulation. We extend the scattering-matrix assembly approach for modeling linear electronic circuits, and motivate it being a viable alternative to the traditional modified nodal analysis approach employed in SPICE-like electronic circuit simulators. Further, we present our approach to support process design kits (PDK) for generic foundries of integrated photonics. It is based on the PDAFlow API which is designed to link different photonic simulation and design automation tools. In particular, it allows design and optimization of photonic circuits for a selected foundry with VPIcomponentMaker Photonic Circuits, and their subsequent export to PhoeniX OptoDesigner for layout verification and GDSII mask generation.

Keywords: photonic integrated circuits, integrated photonics, circuit simulator, process design kits, layout design

1. INTRODUCTION

During the last two decades, 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 is rapidly approaching the order of 1000 components per chip, and is expected to double every 2.5 years [2]. Note that the current level of integration has been reached by micro-electronics by 1969 — during the infancy of the first electronic circuit analysis programs [3]. Remarkably, now we recapture those times once again, living in the beginnings of commercially available photonic circuit simulators [4–9].

In contrast to traditional photonic device 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 photonic building blocks (BBs). Each BB is a photonic device that is coupled to other BBs only via guided modes of optical waveguides — the so-called "optical ports". Because of this, each BB 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 circuit-level modeling of PICs from device-level modeling of photonic BBs. The latter can be performed either using traditional photonic simulators, or employing analytical and behavioral models of photonic BBs. Importantly, different BBs in the same circuit can be modeled by different methods, thus allowing initial rapid prototyping of the circuit and subsequent gradual improvement of the simulation accuracy.

Ideally, the design framework for large-scale PICs should resemble the one developed for electronic circuits (ECs). However, the complexity of photonic circuits greatly exceeds the complexity of electronic circuits in several aspects, thus making the task of photonic design automation very challenging.

First important complication of PICs is the diversity and complexity of their BBs. In electronic circuits we deal with only few types of components, most of them being described by only few parameters. Even complicated components, such as transistors, are described by very simple models compared with the models required for the description of optoelectronic

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and advanced photonic devices (for a similar level of accuracy). The complexity of photonic BBs requires, in particular, to support several simulation models, ranging from very fast idealized to fully realistic measured and highly customizable cosimulated models, describing one and the same BB. Support of fully realistic BB models requires seamless integration between circuit-level and device-level simulators. Physical complexity of photonic BBs requires introducing new "functional" types of model parameters. The need of convenient support of large-scale integration requires extending the traditional hierarchical design approach (which usually includes support of arithmetic parameter expressions) by support of advanced parameter scripting. These challenges and our approaches to their solution are addressed in Section 2.

Another complication is that photonic circuit simulators need to support sophisticated signal models. BBs of ECs are all interconnected by electrical wires, each described by voltage and current, whereas PICs contain, in addition, optoelectronic and photonic devices with optical ports, coupled to each other by optical signals. Due to the spatial inhomogeneity and very high oscillation frequency (around 200 THz) of such signals, they are treated in circuit simulators approximately, as a superposition of guided modes of optical waveguides (device ports), each described by its own complex-valued envelope amplitude, individual for forward- and backward-propagating modes. Moreover, if the optical signals carry several communication channels at different carrier frequencies, one may need to use different envelope amplitudes for each of these channels.

Such sophisticated signal models do not allow extension (in a scalable way) of existing electronic circuit simulators (typically based on SPICE [10]) to PICs modeling. Indeed, to embed the complex-valued envelope amplitude of an optical signal into the modified nodal analysis (MNA) simulation framework, one needs to replace it by an equivalent current and voltage. According to [6], the best approach for this is the usage of magnitude and phase of the envelope amplitude – but in such a representation even simple passive photonic components (like couplers) are regarded as nonlinear devices in terms of the MNA approach. This makes it challenging to add new photonic device models, leads to convergence problems and accuracy degradations as the number of photonic components grows, and thus, makes simulations overall not scalable to large-scale PICs.

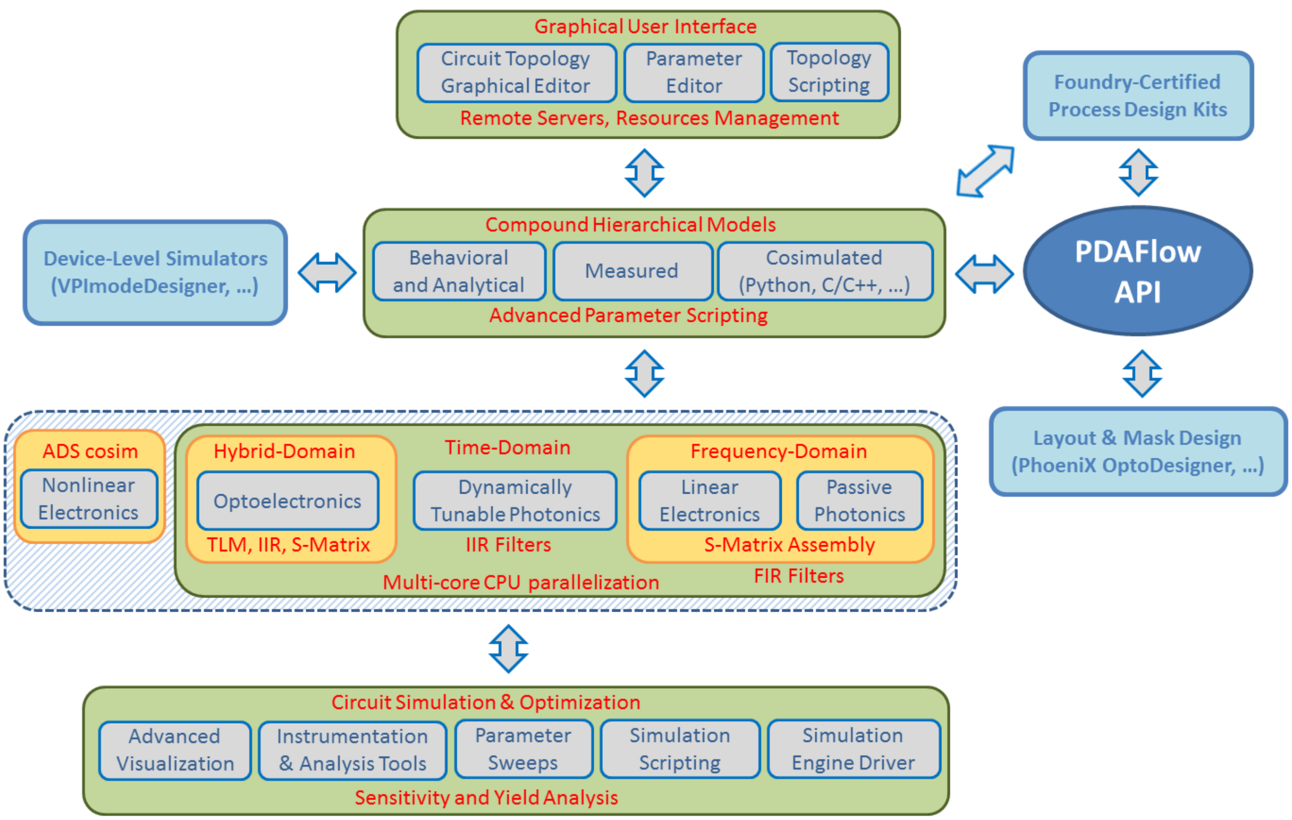


Figure 1. Organization of the circuit-level simulator VPIcomponentMaker Photonic Circuits

Yet another complication is the large variation of BB sizes, which range from sub-microns (waveguide junctions, electronic components) to several centimeters (delay lines). Because of this, some of the BBs should be modeled as lumped devices requiring very small time steps when modeled in time domain. At the same time, lengthy BBs introduce long signal delays, and thus require long simulation times. Special approaches are needed for efficient modeling of spatially distributed tapered and/or dynamically tunable devices.

Consequently, new scalable (fast and at the same time accurate) circuit-level simulation techniques capable of modeling electronic, optoelectronic, and photonic devices on the same circuit, are to be developed. We present an overview of such techniques, developed for VPIcomponentMaker Photonic Circuits, in Section 3.

One of the main goals of an automated design framework is to enable an easy fabrication of the designed circuit. For this, it should provide support of foundry-specific process design kits (PDKs) for both, circuit simulations and subsequent circuit layout (GDSII mask) generation and verification. Our approach to these tasks, based on the PDAFlow API [11], is outlined in Section 4.

The structural organization of VPIcomponentMaker Photonic Circuits is schematically represented in Figure 1. In what follows, we describe in more detail the core functionality of this simulator (its component models and circuit-level simulation engines – see central panels in Figure 1) and its integration with the PDAFlow API (right panels in Figure 1). We will not address here other important parts of the automated design framework, such as the need for a modern graphical user interface (top panel in Figure 1) and advanced optimization, visualization, and analysis capabilities (bottom panel in Figure 1). The interested reader is referred to [7] for more details on our approaches to these parts of the automated design framework.

2. COMPONENTS MODELS AND INTEGRATION WITH DEVICE-LEVEL SIMULATORS

As we have already mentioned, PICs are characterized by a huge diversity of its BBs. Moreover, in contrast to electronic components, each photonic BB can be described by many different models, starting from very simple idealized and sufficiently accurate behavioral, and ending up with fully realistic numerical, based on solving Maxwell's or even more advanced multi-physics equations. Correctly addressing all these BBs and their different models imposes the first challenge on photonic circuit simulators, making them quite different from EDA tools. We employ several approaches to address this problem in VPIcomponentMaker Photonic Circuits.

2.1 Built-in and measured photonic components

First, we support quite a broad set of built-in photonic BBs, and most of them can be described by several models. As an example, the directional coupler "WgXCoupler" can be modeled as an idealized lumped coupler, characterized by only a single parameter – CouplingPowerRatio (with the only complication that it may be different for different modes). Such a simple model is ideal for quick prototyping of, for instance, Mach-Zehnder modulators, multi-ring resonators, and optical interleavers. However, when required, the model of directional coupler can be switched to apply a very accurate model derived from the coupled-mode theory – and then one can account for group delay and group velocity dispersion, study the effects of mode beating versus coupling length and waveguides detuning, and other effects. Clearly, such a more complicated model requires knowledge of a larger set of parameters, starting with polarization- and frequency-dependent effective mode indices and attenuations, and ending with polarization-dependent coupling coefficients describing the overlap between modes of two coupled waveguides. This coupled-mode theory model is ideal for theoretical physicists – properly setting the values of all its parameters, they can very realistically model almost any directional coupler and easily explore the role of each parameter or the effects of statistical parameter variations. However, the extraction of these parameters for reproducing a specific custom device would be too cumbersome for experimentalists. For them, we provide the so-called "Measured" model, which allows loading the frequency-dependent S-matrix of the modeled device from file. Such an S-matrix may be either measured experimentally (together with its phase information) or extracted from numerical FEM, BPM, or FDTD simulations. Further, it can include any real-world complications, such as polarization coupling and back-scattering due to roughness of waveguide side walls or other fabrication imperfections.

Most of built-in photonic BBs support accurate analytical models based on the coupled-mode theory, Fourier-optics analysis, or self-imaging theory, all of which require knowledge of the frequency-dependent effective mode indices and attenuations for underlying channel or planar waveguides. The presence of many frequency-dependent (or intensity-dependent) parameters in photonic BBs imposes yet another significant complication to photonic simulators in comparison with EDA tools. Commonly, such dependent parameters are described by one or few predefined functional dependencies (or, very often, by a Taylor series expansion) – which results in introducing several more model parameters. Using this approach the frequency-dependent effective mode index, for example, is described by effective index, group index, and dispersion (sometimes also dispersion slope) at a certain reference frequency. This gives accurate effective index fitting in the range of several tens of terahertz, and thus is acceptable for most PIC applications, except for wavelength-division multiplexing (WDM). The latter requires a more broadband effective mode index, usually covered by loading data from file (so-called “Measured” effective index model), accompanied by introducing additional model parameters for setting data file name and switching between “Measured” and “Taylor” models. Consequently, each new predefined functional dependence for a single parameter requires adding one or several new model parameters.

To resolve this problem, we have introduced a new type of model parameters – the so-called “functional parameters”. With this concept, a single functional parameter can either describe the required functional dependence by a user-defined Python script (not just an arithmetic expression, but an arbitrarily complex script which can also import external Python libraries), or load it from a data file. In the latter case, the name of the loaded data file can also be pre-computed by a Python script, which can even create the missing data file “on-the-fly”, according to the values of other simulation parameters (say, extract the data for a given temperature from an external database or load it from the Internet).

Such functional parameters can be used not only for defining arbitrary frequency-dependent effective mode indices and attenuations of waveguides, but also for defining arbitrary apodization and chirp profiles for waveguide Bragg gratings, arbitrary patterns of sampled Bragg gratings, arbitrary nonlinear transfer functions for power-dependent optical and electrical components. We believe that systematic usage of functional parameters will allow to significantly simplify the interface of photonic and optoelectronic BBs and at the same time make them even more flexible and powerful in terms of the supported simulation models.

2.2 Compound (hierarchical) photonic components

Photonic design automation, similar to EDA, is not feasible without support of a hierarchical design approach. It should be possible to easily reuse once created and verified sub-circuits as compound BBs in the same way as we employ built-in BBs (in particular, it should be possible to use compound BBs inside other compound BBs, and thus, allowing arbitrary number of hierarchical levels). This sounds very similar to what is currently supported in EDA tools – but in reality, PIC design automation imposes much more challenging requirements on the capabilities of its hierarchical design approach.

Let us illustrate these requirements by the example of a multi-ring add-drop optical coupler, shown in Figure 2(a).

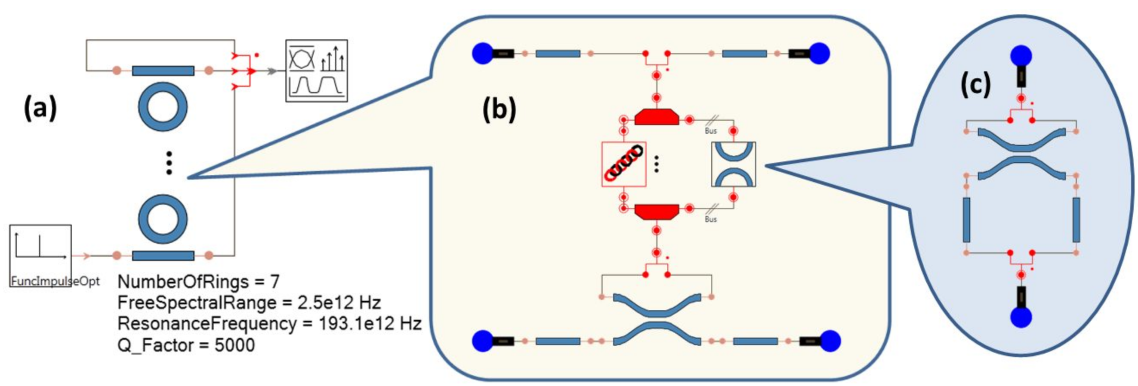


Figure 2. Multi-ring add-drop optical coupler modeled as a compound BB with advanced parameter scripting

Ideally, we wish to describe such a multi-ring coupler by the same set of parameters that we use for the built-in single-ring coupler. This includes the switch parameter “DesignMode” which allows users to define the design parameters by either “StructureParameters” (such as ring radii, coupling coefficients, ring phase shifts, etc) or “ResonanceParameters” (such as free spectral range, resonance frequency, resonance quality factor, etc). We also wish to switch the number of rings inside the modeled filter by simply changing the value of the integer parameter “NumberOfRings” instead of creating (and subsequently maintaining) a multitude of similar BBs with different number of rings. We require that coupling between different rings should be automatically adjusted in such a way that the filter will have a maximally flattop passband. But still, we would like to be able to account for fabrication tolerances and thus perform yield optimization for PICs which will employ such multi-ring filters (note: increasing the number of rings improves flatness of the filter passbands, but increases sensitivity to fabrication imperfections). Finally, this multi-ring filter should be a compound BB, meaning that it should consist of waveguides and couplers modeled by verified built-in BBs, what seems to be infeasible applying the traditional hierarchical design approach.

However, using VPIcomponentMaker Photonic Circuits this challenging task can now be performed in a straightforward way, as illustrated in Figure 2. First of all, we provide a set of the so-called "High-Order Function" modules which allow to replicate connected BBs either in a chain (as required for multi-ring filters, see Figure 2-b) or in an array (as required for arrayed waveguide gratings with hundreds of different waveguides between two star couplers, see Figure 4). This allows not only to replicate the BBs, but also to individually specify the values of their parameters.

Second, we support advanced scripting mechanisms for setting the values of parameters for all underlying BBs according to the chosen values of the designed compound BB. The values of any parameters (not only functional ones) can be evaluated using not only standard arithmetic parameter expressions, but also Python scripts of arbitrary complexity. In particular, setting the correct values for the coupling coefficients in our flat-top multi-ring filter example requires numerically solving a complex system of nonlinear equations – which in our case can be easily performed by calling a function from the scipy.optimize Python library. The support of Python scripting for setting module parameters allows us also to incorporate many different simulation models into a single compound BB. For our example case, this enables designing the multi-ring filter either according to its desired resonance properties, or according to the geometrical structure parameters of its waveguides and couplers.

Additionally, our implementation of the advanced hierarchical design approach provides support of the "Measured" simulation model and functional parameters, and thus, allowing to rapidly create compound BBs with a very advanced functionality, fully equivalent to the functionality of built-in BBs.

Designed in such a way, the compound BBs may incorporate significant intellectual property (IP) which designers may wish to protect. For this, we provide a built-in encryption mechanism which hides all the sensitive information about circuit topology and its internal parameter values (including encryption of all the internal Python scripts), but still allows other users to apply such BBs in their simulations.

2.3 Cosimulated photonic components

The advanced hierarchical design approach described above allows to efficiently increase complexity of the designed photonic circuits. However, it requires that a sufficiently large number of BBs which perform all kinds of basic functionality do already exist. And although we provide quite a broad set of the built-in BBs, they cannot cover all the required basic functionality considering the huge diversity of possible photonic BBs.

Because of this, an important part of the automated photonic design framework is the possibility to easily add new single-entity BBs covering missing functionality. We provide such a possibility by supporting two interfaces for creating the so-called "cosimulated" BBs.

The first cosimulation interface allows creating linear photonic and electrical BBs which can be described by frequency-dependent scattering matrices (see Sections 3.2 and 3.6). For such BBs, users need only to define a Python or C++ class which can be initialized with the BB parameters and provides the method for calculating the device S-matrix at any given frequency and for any given combination of input and output ports and modes. The second cosimulation interface allows modeling of arbitrary active, nonlinear, or dynamically tunable BBs by writing functions (in Python, MATLAB, C/C++/Fortran, or others) which process input signals, and produce output signals either in frequency or time domain.

2.4 Integration with device-level simulators

An important part of an automated photonic design framework is a seamless integration of circuit-level and device-level photonic simulators. The main purpose of such an integration is to avoid switching back and forth between different types of simulators when users need to perform, as an example, yield analysis of the designed PIC with respect to given fabrication tolerances for thicknesses and widths of different layers in the waveguide cross-sections. If such waveguides are modeled in the circuit simulator by our built-in waveguide models, they are described in terms of frequency-dependent effective mode indices, attenuations, and mode coupling coefficients. Potentially, these functional parameters can be calculated in advance with device-level simulators for specific parameter values, cached or fitted, stored into databases, and then reused in the circuit-level simulator. This approach is appropriate if the number of varying parameters describing the device is sufficiently small (say, waveguide temperature, width, and bend radius). However, as the number of variable process parameters grows, it becomes more and more difficult to support an approach based on pre-calculated databases. To resolve this problem, the circuit simulator should be able to not only rapidly extract the required simulation parameters for the given device layout from the pre-calculated database, but also to automatically start the appropriate device-level simulator and update the database with new data, if they were missing.

Our approach to the integration of VPIcomponentMaker Photonic Circuits with device-level simulators is based on support of advanced parameters scripting using Python (described in Section 2.2), on the one hand, and on support of several cosimulation interfaces (described in Section 2.3), on the other hand. Since Python comes with a very rich support of different databases, links to Microsoft Excel, COM interface, and more, it allows to easily establish any desired level of seamless integration with virtually any device-level simulator which supports a command-line or scripting interface.

However, to minimize efforts for configuring such an integration, the employed device-level simulator should best of all support a user-friendly native Python interface and be accompanied by its own set of most common tasks required by the circuit simulator: calculation and automatic fitting of frequency-dependent effective mode indices and attenuations, coupling coefficients, effective mode area, mode spot-sizes, and other parameters required by built-in models of photonic and optoelectronic BBs.

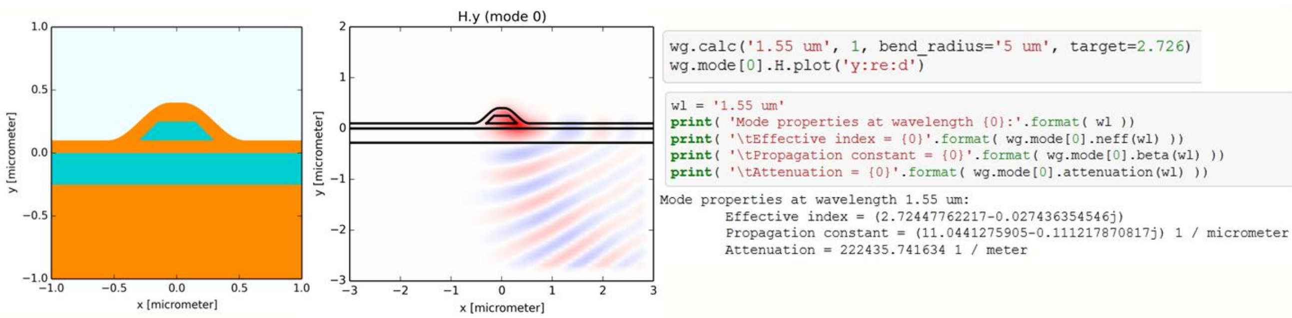


Figure 3. Application of VPImodeDesigner for calculation of the TE mode properties for an integrated optical waveguide with a complex smooth cross-section shape and power leakage due to both, high-index substrate and waveguide bend

To accomplish the needs for such a device-level simulator, we developed VPImodeDesigner (illustrated in Figure 3) – a versatile simulation framework which supports advanced layout definitions of integrated photonic waveguides and related devices, and facilitates their analysis and optimization via a powerful Python interface. It implements full-vectorial finite-difference mode solvers with support of widely customizable non-uniform meshing and perfectly matched layer absorbing boundaries. It supports isotropic and anisotropic dispersive and lossy optical materials, and allows calculating modes for planar or straight and bent channel waveguides. Finally, it provides advanced visualization and field analysis capabilities, native support of physical units, and a set of functions and classes which simplify the integration between VPImodeDesigner and VPIcomponentMaker Photonic Circuits.

3. CIRCUIT-LEVEL SIMULATION ENGINES

At the heart of any photonic circuit simulator reside its circuit-level simulation engines, which to a large extend determine the main capabilities and limitations of the simulator. VPIcomponentMaker Photonic Circuits supports several different circuit-level simulation engines which can be mixed together in the same circuit simulation.

3.1 Frequency-domain approach to modeling passive photonics

A great majority of photonic components that comprise PICs are passive. That is, they operate as purely linear photonic devices whose output optical signals are produced as superposition of filtered input optical signals. Their analysis can best be performed, in the frequency domain. In this case, each passive BB is completely described by a frequency-dependent scattering matrix (S-matrix) that relates amplitudes of incoming and outgoing guided modes at all device ports [12]. The advantage of this approach is that the system response can be calculated for each signal frequency independently, and thus, allowing efficient parallelization of simulations and high accuracy for even narrow-band input signals.

Fully passive sub-circuits which can be described by a uni-directional signal flow (such as an arrayed waveguide grating, as illustrated in Figure 4) can be described in a straightforward way by filtering the optical signals in frequency domain, one component after another.

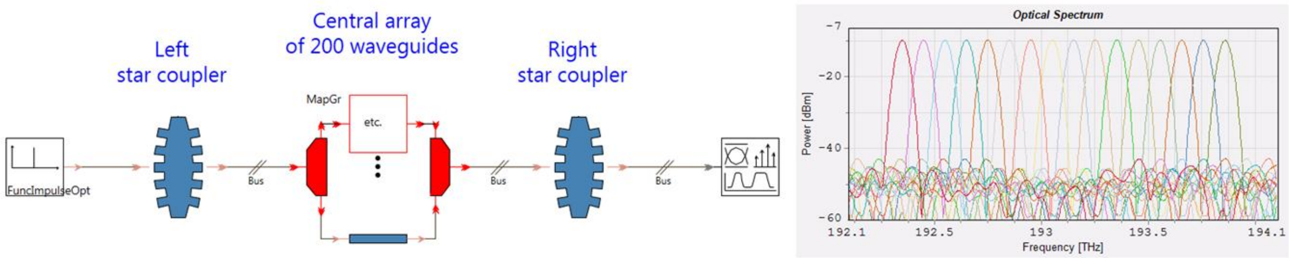


Figure 4. Schematic illustrating modeling of non-reflective 1x16 AWG with an array of 200 waveguides (left), and exemplary spectral responses of each of the 16 paths through the AWG (right)

3.2 Scattering matrix assembly technique

The straightforward frequency-domain approach is not applicable as soon as the modeled passive sub-circuit contains back-reflections and/or feedback loops. The properties of such sub-circuits can be described by recursive combinations of the S-matrices of individual BBs into a single S-matrix representing the complete sub-circuit [13], and subsequent signal filtering in the frequency domain. This approach is illustrated in Figure 5 for an example system that consists of two coupled silicon ring resonators with 10 microns diameter – each ring resonator is modeled as a compound passive BB made of two couplers and two bent waveguides, as outlined in Section 2.2. Due to coupling between the two rings, such a system exhibits the effect of coupled-resonator-induced transparency (notice a high-quality transmission line in the “Through” spectrum on Figure 5, right).

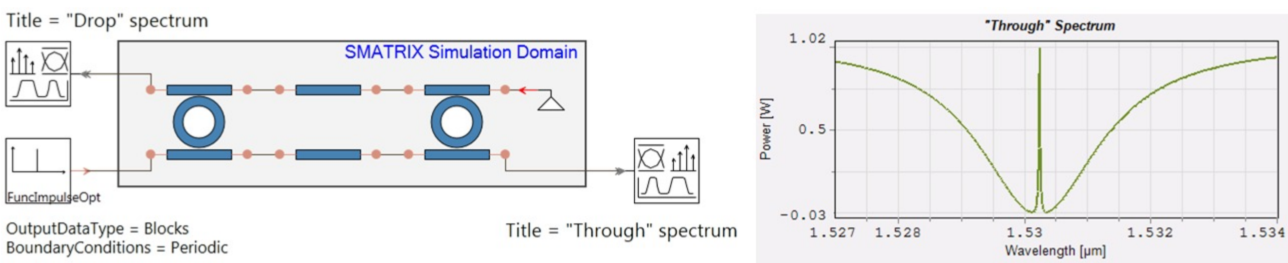


Figure 5. Schematic illustrating the modeling of coupled-resonator-induced transparency in SMATRIX simulation domain (left) and exemplary spectral response exhibiting a very narrow transmission line (right)

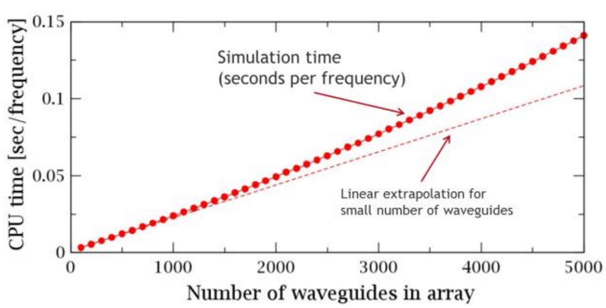


Figure 6. Scaling of the simulation time in SMATRIX domain with the number of arrayed waveguides for an AWG design case with back-reflections

In what follows we refer to this approach as the “Scattering matrix assembly technique” or “SMATRIX simulation domain”. Numerically, the problem is reduced to solving a sparse linear system. Importantly, different types of passive sub-circuits require different types of linear system solvers to gain the best simulation speed. Employing several iterative solvers with several advanced preconditioners, and an automatic selection of the fastest solver for a given sub-circuit allows a very fast and highly precise analysis of passive PICs [14], easily scalable to circuits with thousands of passive components (see Figure 6).

3.3 Time-domain approach and its limitations

All the advantages of the scattering matrix assembly technique fade away as soon as the modeled photonic circuit includes non-passive BBs which cannot be described in frequency domain.

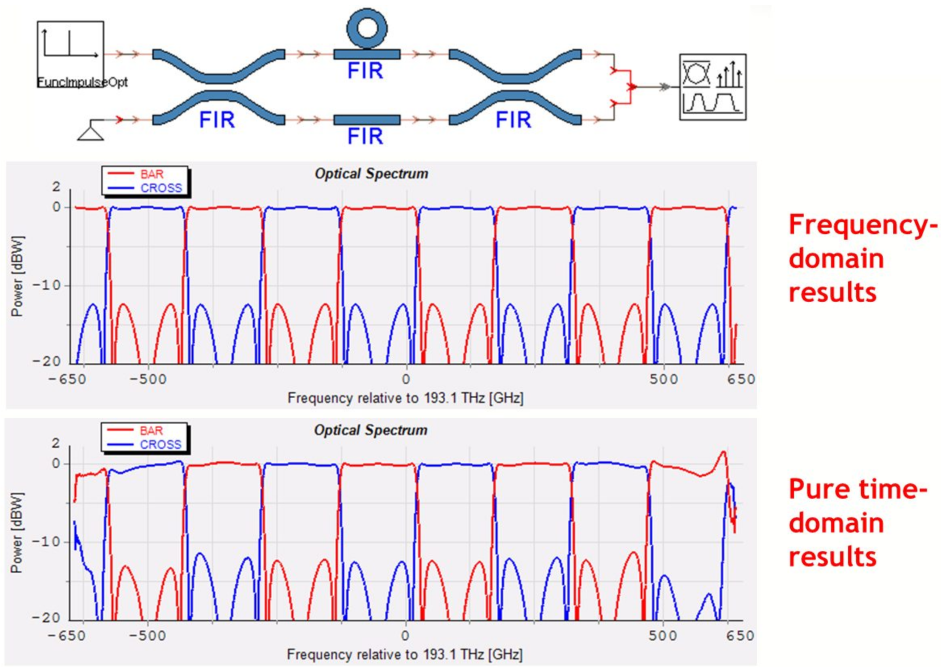


Figure 7. Illustration of the accuracy of the pure time-domain simulation approach for small-scale PICs

Modeling of non-passive PICs is commonly performed in time domain. In this case, all the BBs that comprise such PICs are modeled in time domain – *including each of the linear BBs*, even if the modeled PIC contains only a single non-passive component. Theoretically, the time-domain modeling of linear BBs 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. And 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 BBs (see illustration in Figure 7, where results remain accurate for a sufficiently broad frequency range around the center of the signal band).

However, due to multiplicative effects, the net bandwidth where simulation results remain accurate rapidly decreases as the number of BBs in the simulated PIC increases. This is illustrated in Figure 8, where the optical interleaver from Figure 7 is repeated *N* times. Despite the absence of back reflections, high-quality resonances or other complications in the modeled passive sub-circuit, the accuracy of its time-domain simulations rapidly degrades and eventually collapses at the final number *N* of interleavers.

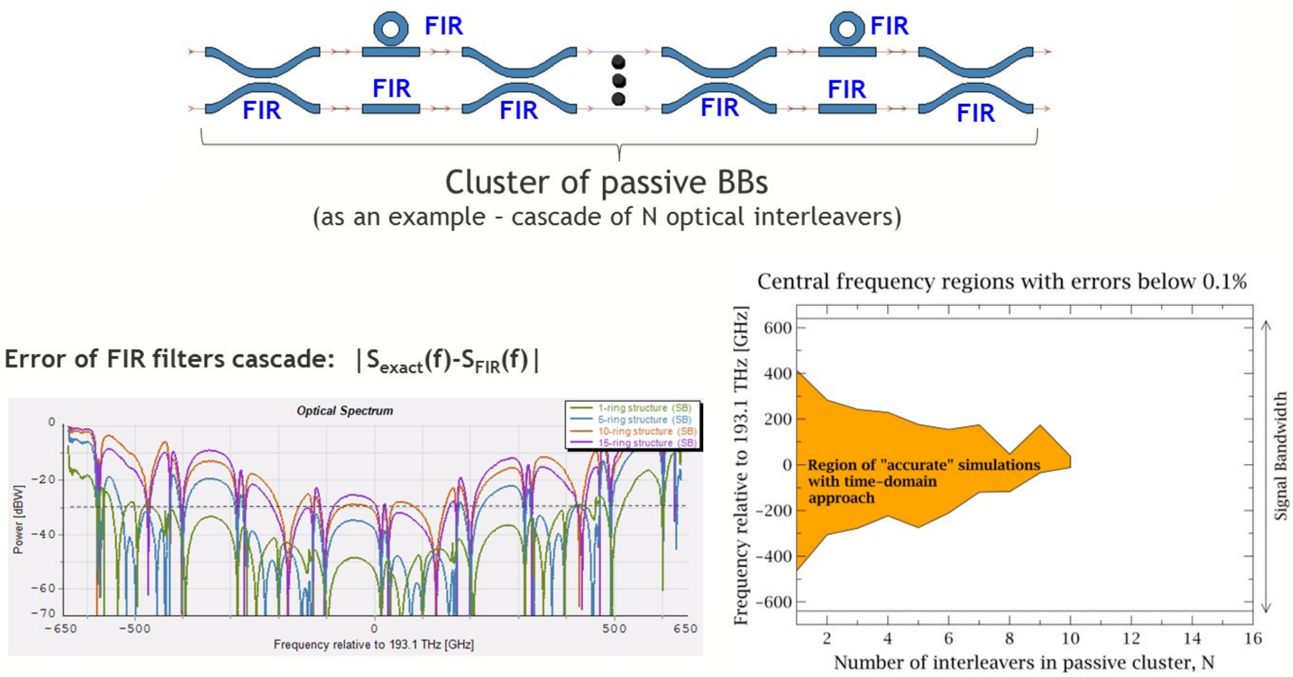


Figure 8. Illustration of fast accuracy degradation of the pure time-domain simulation approach for large-scale PICs

This problem becomes even harder in the presence of short-length BBs (for example, small microrings or waveguides connecting neighboring devices) since their short impulse responses require smaller time steps for accurate modeling and increased computational 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, and 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 BBs exceeds several tens.

3.4 Hybrid time-and-frequency-domain approach

To overcome the aforementioned limitations we have developed a hybrid time-and-frequency-domain simulation approach [7]. Within this approach, all passive sub-circuits are first modeled in SMATRIX simulation domain and, therefore, they are automatically (and transparently for users) replaced by single-entity passive devices. Then the FIR filters are calculated (again fully automatically) for only such passive sub-circuits, but not for each individual passive BB, as it happens in the standard time-domain approach. In practice, the number of such passive sub-circuits will be comparable with the number of non-passive BBs – which is usually many times smaller than the total number of passive BBs.

The accuracy of this approach is illustrated in Figure 9, for exactly the same example as was considered in Figure 8. As can be seen, the bandwidth of accurate simulations not only stops to decrease with growing number N of optical interleavers, but, in contrast, is enlarged and quite soon starts to occupy almost the whole signal bandwidth. This is caused by the fact that the accuracy of FIR filters is mainly determined by the minimal group delay accumulated by the transmitted signal: the larger it is in comparison with the simulation time step, the more accurate are the properly designed FIR filters.

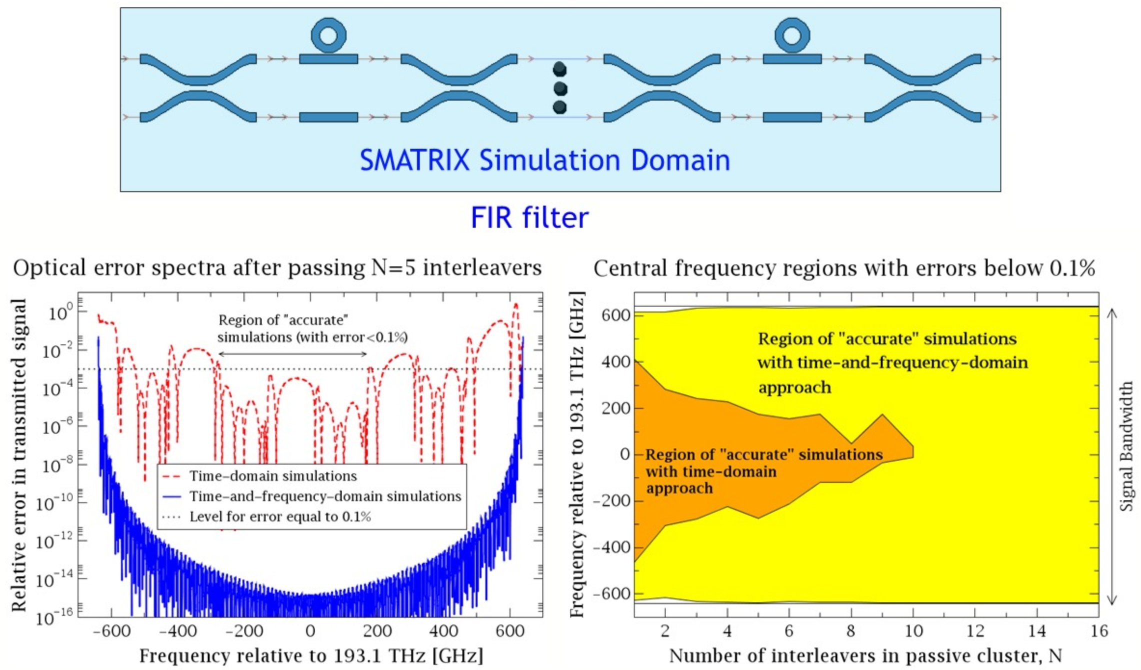


Figure 9. Illustration of high accuracy and scalability of the hybrid time-and-frequency-domain simulation approach for large-scale PICs

3.5 Approaches to modeling multi-section optoelectronic devices

Time-domain modeling of active BBs is quite simple as long as we are satisfied with the simplified physical models.

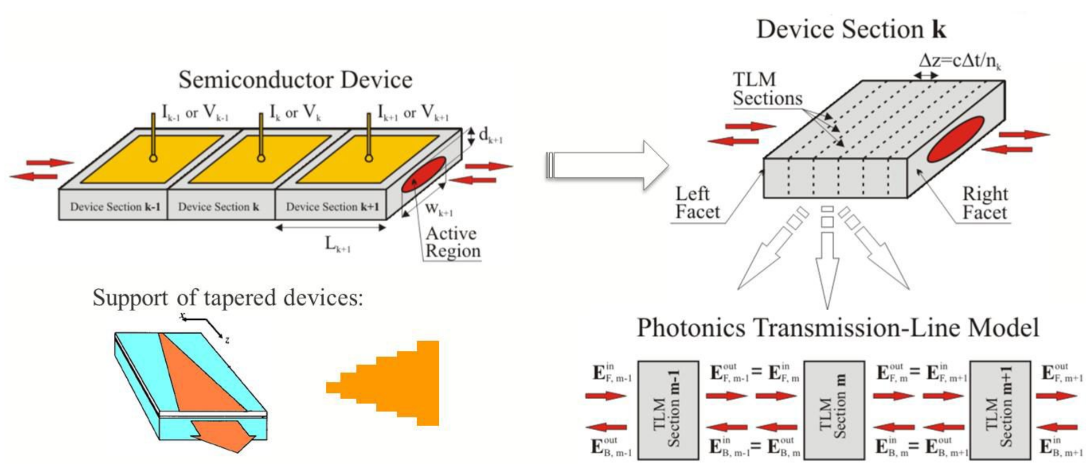


Figure 10. Simplified representation of the PhotonicsTLM model for the realistic modeling of advanced multi-section optoelectronic devices

However, realistic modeling of distributed optoelectronic devices introduces significant complications, and hence cannot be performed with standard time-domain simulations [15]. A combination of new, sophisticated simulation techniques is required which are even more complicated than the hybrid time-and-frequency-domain approach outlined above.

We developed and embedded appropriate simulation techniques in the PhotonicsTLM model of VPIcomponentMaker Photonic Circuits, which allows very realistic and accurate modeling of a wide range of distributed optoelectronic devices. A simplified representation of the PhotonicsTLM model (historically based on the transmission-line modeling approach) is depicted in Figure 10. As can be seen, it supports simulation of multi-section devices, where each device section is characterized by its own geometrical and material parameters, and can be driven by its own injection current or inverse-bias voltage. With this the modeling of any tapered (but yet single-mode) optoelectronic device can be performed as well. Each device section is divided into a set of small TLM subsections, characterized by a constant carrier density and exponentially decaying (or growing) optical fields, and thus, allowing to account for spatial hole burning and related effects.

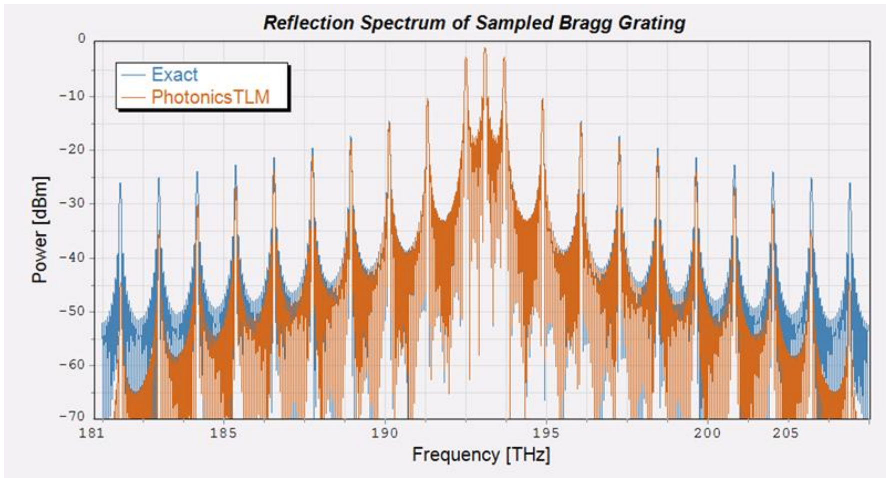


Figure 11. Transfer function of a sampled Bragg grating simulated approximately by PhotonicsTLM model and accurately with the frequency-domain approach. Notice the good accuracy around the center of the simulated signal band.

An embedded scattering-matrix treatment of lumped reflective facets between device sections and of distributed index or gain/loss gratings allows accurate modeling of both, Fabry-Perot and DFR/DBR lasers. As an illustration, Figure 11 shows the spectrum of a sampled Bragg grating modeled inside the PhotonicsTLM in comparison with the exact spectrum using frequency-domain simulations.

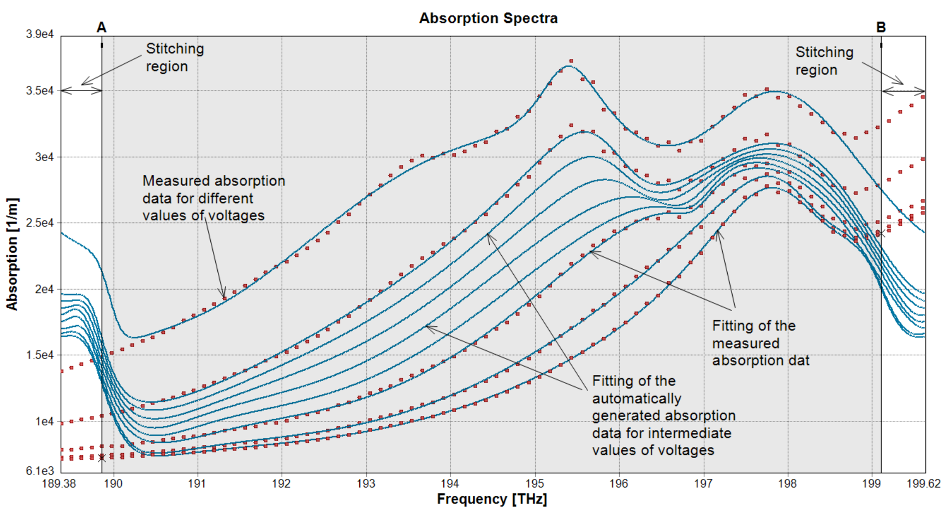
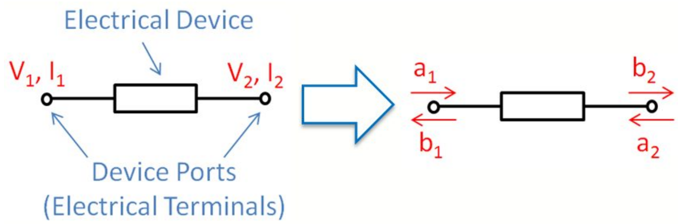


Figure 12. Automatic fitting of measured voltage-dependent electro-absorption spectra by PhotonicsTLM model using 6-th order IIR digital filter

Models of MQW and Bulk active regions incorporate all the main physical effects such as free-carrier absorption (FCA) and free-carrier dispersion (FCD, or plasma effect), Kerr nonlinearity and two-photon absorption (TPA). For quick prototyping, the carrier-dependent gain and voltage-dependent electro-absorption can be modeled using simplified analytical gain/absorption spectra shapes. For fully realistic simulations, the measured spectra can be loaded from files and automatically fitted by high-order IIR filters, as we illustrated in Figure 12.

3.6 Scattering matrix approach to modeling linear electronics

An important remaining challenge is the integration of photonic and electronic simulations within a single circuit-level simulator. As we have already discussed in Section 1, one approach to solve this problem is based on the extension of the MNA method, applied for instance in the OptiSPICE simulator [6]. This approach, however, makes it very challenging to embed new accurate simulation models for photonic and optoelectronic components. Moreover, this approach suffers from the same poor scalability problems as the pure time-domain approach outlined in Section 2.3.



$$a_n = \frac{1}{2}\left(\frac{V_n}{\sqrt{R_0}} + \sqrt{R_0} I_n\right)$$

$$b_n = \frac{1}{2}\left(\frac{V_n}{\sqrt{R_0}} - \sqrt{R_0} I_n\right)$$

Figure 13. Standard electrical device description in terms of terminal voltage and current (left), and it alternative description in terms of incoming and outgoing waves (right)

As an alternative, we extend the above outlined simulation approaches to photonic and optoelectronic circuits so that they will also incorporate the native modeling of linear and nonlinear electronic components. For this, we describe all the terminals of electrical devices not by their voltages and currents, but by the amplitudes of the incoming and outgoing electrical waves, as it is shown in Figure 13. As a result, any linear electrical device can be characterized by an effective scattering matrix, and therefore modeled by employing the same scattering matrix assembly technique as we have developed for modeling passive photonic circuits (see an illustration in Figure 14).

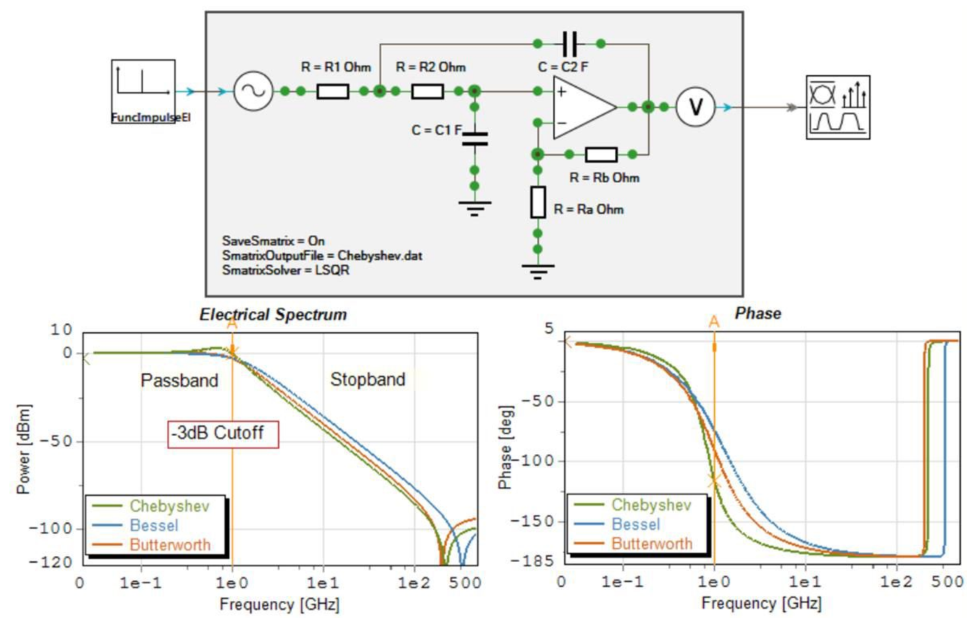


Figure 14. Application of the SMATRIX simulation domain to design active linear Sallen-Key electrical filters

We demonstrate that although the S-matrix approach is numerically less efficient than the MNA method when applied to purely electronic circuits, it enables modeling of electronic circuits with exactly zero or infinite values of resistance, capacitance and inductance. Further, it supports modeling of ideal toggle switches, ideal transformers, and other linear circuits. Since even grounds and electrical nodes are represented by their own S-matrices, one can easily incorporate parasitic current leakage, back reflections of rapidly modulated signals and other effects.

The incorporation of the native modeling of nonlinear electronic components into VPIcomponentMaker Photonic Circuits remains an open challenge: it requires the development of a new extended simulation engine which supports the modeling of interconnected lumped nonlinear elements.

Another important challenge is the development of a time-domain interface between VPIcomponentMaker Photonic Circuits and common SPICE simulators.VPIcomponentMaker Photonic Circuits supports already interfacing with the Keysight (Agilent) ADS simulator. However, cosimulation is still limited to block signal simulations, and thus, cannot account for the feedback spanning both, photonic and electronic parts of hybrid circuits.

4. SUPPORT OF PROCESS DESIGN KITS AND MASK LAYOUT DESIGN

The simulation framework outlined in the previous Sections provides users with a very flexible design environment, which allows to start PIC design with idealized components, rapidly get a working system-level circuit prototype, and gradually replace idealized components with fully realistic ones, exploring the role of fabrication imperfections, and performing optimization and yield analysis. Therefore, it is well suited for academic and industrial researchers who explore new principles of circuit design, roles of different physical effects, and tolerances. It is also very fruitful for educational purposes.

However, the flexibility of such a design approach appears to be excessive for applied PIC designers whose main aim is to rapidly design an optical chip with certain prerequisite functionality, which can be fabricated on a specific foundry with a guaranteed yield. Cost-efficient and reliable fabrication of integrated photonics requires standardization of all the processes and photonics BBs supporting them in the form of process design kits (PDKs). Fabrication is a complex multi-step process which requires, in particular, usage of many different software tools – an efficient integration of all these tools, and their ability to work with the same PDK, is of key importance. For this, PDKs developed by different foundries require standardization in their turn: they should support the same application programming interface (API) so that different software vendors and different photonics foundries are able to interface with each other, avoiding duplication of work and fragmentation of the growing integrated photonics market.

PDK standardization in electronics is performed by the Si2 (Silicon Integration Initiative) organization which associates over 100 industry-leading companies in the semiconductor, electronic systems and EDA industries. They develop, in particular, the OpenAccess API for enabling tightly-integrated, multi-vendor tool flows through an open standard PDK data. In photonics, the same goals are addressed by the recently formed PDAFlow Foundation [11], which currently associates seven companies and is actively developing the PDAFlow API for automating photonics design flows and creating sustainable PDK standards. Currently, this API is supported (at different levels) in PDKs from eight different integrated photonics foundries. In the framework of these efforts, VPIcomponentMaker Photonic Circuits has been extended to support the foundry-specific PDKs through the PDAFlow API.

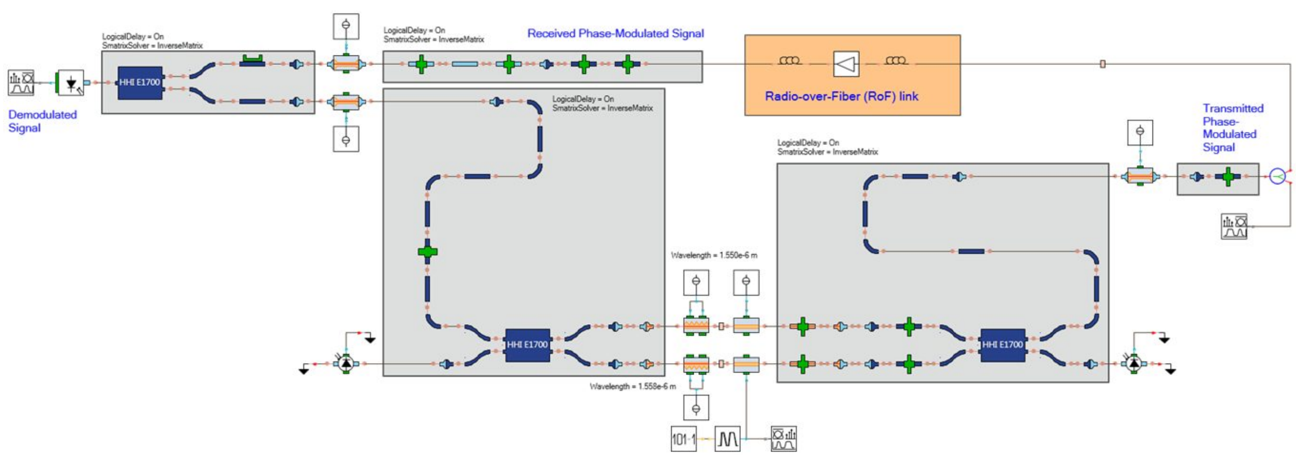


Figure 15. Example of the receiver and transmitter PIC for THz applications designed using specialized BBs from the PDK HHI toolkit of VPIcomponentMaker Photonic Circuits

From the circuit simulation point of view, each PDK is a library of BBs which can be fabricated at a given foundry. Internally of VPIcomponentMaker Photonic Circuits, each of these BBs is represented as an encrypted compound (or cosimulated) BB. Consequently, it can fully employ the flexibility of the advanced simulation framework described in the previous Sections to elaborate fast and accurate simulation models for every active or passive photonic component.

From the users perspective, however, each BB is characterized by only a few parameters (width and length for a straight waveguide, for instance). This enables a very rapid design of PICs with the desired functionality and the guarantee that it can be fabricated at a given foundry.

As an example, Figure 15 illustrates the circuit design for an integrated transmitter and receiver PIC for THz applications based on the generic integration technology developed at the Fraunhofer Heinrich Hertz Institute (HHI). This design is based on the specialized BBs from the PDK HHI toolkit library, developed for VPIcomponentMaker Photonic Circuits. After finishing the design and optimization of this circuit with our simulator, one can easily export its layout to the PhoeniX OptoDesigner [16] (see Figure 16-a). Then, using OptoDesigner, one can fit the designed chip layout into the desired die packaging, add proper electrical wires routing, perform DRC verification, and export the final GDSII mask for optical chip fabrication (see Figure 16-b).

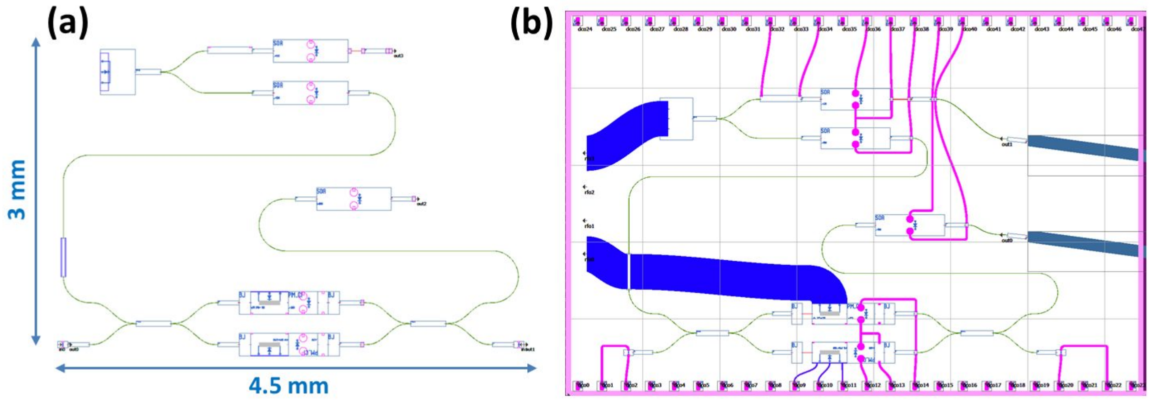


Figure 16. Layout for the circuit from Figure 15 after (a) its automatic export from VPIcomponentMaker Photonic Circuits to PhoeniX OptoDesigner and (b) final mask generation after its packaging and electrical wires routing with OptoDesigner.

Such kind of interoperability between different photonics design tools enables to greatly speed up the PIC design process, and thus, significantly reduce costs of integrated photonics for the end users.

5. CONCLUSION

We presented an overview of important challenges associated with the development of an automated design framework for large-scale photonic integrated circuits (PICs), and explained how we address these challenges in VPIcomponentMaker Photonic Circuits. Two prominent challenges which we consider being of key importance to overcome are the photonic-electronic codesign and the entanglement between circuit design and layout design. The first challenge has briefly been discussed here and recently reviewed in detail in [17]. The second challenge is not yet a subject of hot public discussions, but will soon become the main challenge. For PICs, it is not possible to separate the circuit design from the layout design. Both design tasks should be performed together, at the same time – and this will require much closer integration between circuit-level simulators and layout design tools than it was ever required for the electronic design automation framework. Specific objectives and principles of such integration still need to be identified and elaborated.

Summarizing, we state that due to the superior complexity of PICs in comparison to electronic circuits, there are no simple and straightforward ways for extending well elaborated EDA tools to satisfy the needs of integrated photonics. This task requires the development of specialized photonic circuit simulators, and initiated active research towards this direction during the past several years. Integrated electronics needs to be regarded as a subset of integrated photonics, not vice versa. And because of this we believe that it will be very challenging for EDA tools, despite of their maturity, to integrate directly functionality for photonic design automation. We believe that new versatile and comprehensive PDA tools will integrate with EDA tools to offer a complete automated design framework for large-scale heterogeneous PICs.

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