

Photonic Component Design Libraries and Fast Circuit Simulation

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In a Generic Integration Technology many different functionalities can be supported by combining basic building blocks in different ways. Because the technology platform is well defined, and semi-fixed between releases, library based design methods are well suited for designing circuits in such a technology. Library based design reduces design time and allows for higher circuit complexities. In this paper we describe the progress being made on a library of passive components in the EU project PARADIGM. Furthermore, we discuss a method to achieve a significant speed-up in circuit level simulations.

Introduction

In electronics a broad range of functionalities is supported by a small set of basic building blocks. In photonics something similar is possible [1]. This means that a technology platform that supports the basic building blocks automatically supports the wide range of functionalities that can be accomplished with these building blocks [2]. In a Generic Foundry model, foundries offer access to a well defined, stable generic integration technology. Between versions these technology platforms are frozen, meaning the process does not change. This makes it feasible to develop not only basic building blocks, but also composite building blocks for these technologies. These building blocks can be provided to users in the form of component libraries. The first part of this paper investigates the features needed from these libraries by looking at the specific case of a passive component library. The second part concentrates on a method for very fast circuit simulation.

Designing a Photonic Circuit

Designing a photonic circuit usually consists out of iterating over three phases: circuit description, circuit simulation and circuit layout. The design process is illustrated in Fig. 1. During every phase the component libraries play a role. In this section we will highlight this role.

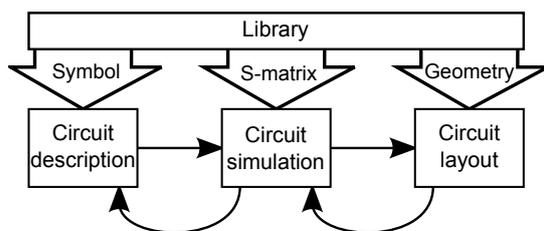


Fig. 1: Design phases

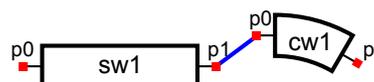


Fig. 2: Circuit description of a straight waveguide (sw1) and a curved waveguide (cw1). Port p1 of sw1 is connected to p0 of cw1.

Circuit Description

At the circuit level, every building block is represented by a symbol and has a number of ports. It is assumed that components can only couple via these ports. This is a reasonable assumption when the radiation fields are small [3]. The symbol for a building block and the port position and properties (number of modes, etc.) are defined in the library. A designer creates a circuit by defining connections between ports (Fig. 2). All connections are stored in a netlist. The netlist represents the entire circuit.

Circuit Simulation

To get the response of the full circuit, the netlist is offered to a circuit solver. When non-linear effects play a role, a time domain based solver is used [4]. When the circuit is assumed to be linear, a frequency domain solver can be used. Here we focus on passive, linear components. Therefore only the frequency domain approach will be discussed.

In the frequency domain, the response of an N -port component is described by an $N \times N$ scatter-matrix (S-matrix). To illustrate the S-matrix approach we look at a mono-mode straight waveguide. Such a waveguide is a two-port component. Its response is described by $S_{21} = S_{12} = \exp(-j\beta L)$, with β the propagation constant and L the waveguide length. Similarly, a curved waveguide is described by $S_{21} = S_{12} = \exp(-j\beta_\phi \phi)$, with β_ϕ the angular propagation constant. Because there are no reflections inside the waveguide, $S_{11} = S_{22} = 0$. Using the netlist, the circuit solver concatenates the S-matrices of all the components to get the circuit response. The contents of the S-matrix of each building block is provided by the component library. These values could be obtained through rigorous electromagnetic simulation, measurements or a model.

Circuit Layout

After circuit simulations have verified that the circuit will behave in the desired way, the designer can proceed with making a layout of the circuit. In principle the layout can be generated automatically from the netlist. However, performing circuit layout in practice means trying to fit the design to a certain area and meeting other geometrical requirements. These are things normally not considered when making a description of the circuit. In practice there will be large functional blocks, like an Arrayed Waveguide Grating for example, that are connected to other components using waveguides. The lengths of these connector waveguides are not known until the layout phase. Though they are usually relatively low loss, the connector waveguides can still have a profound influence on the circuit behaviour through their phase response. After the layout step, the response of the circuit has to be verified again. It is therefore important that the netlist can be easily updated with the new geometrical information.

Library Requirements

When looking through the previous section we see that there are three clear phases in designing a circuit. The component library plays a role in all of them. Circuit designers put very high trust into library components. If a component is in the library one can assume that it works well. Therefore a lot of characterization work must be done on every component before it is allowed into the library [5].

Reducing circuit simulation time

Previously it was mentioned that the response of a waveguide can be generated from the modal propagation constant β and the waveguide length. Finding β for all modes, for all waveguides in a circuit, at all wavelengths of interest can be a computationally heavy task. This is especially true for curved waveguides.

A fixed technology allows to calculate a lot of values in advance, thereby speeding up circuit simulations significantly. As a first step we investigate how the propagation constants of guided modes can be precalculated for straight ridge waveguides. Because the layer stack and etch-depth are fixed, the propagation constant varies only with mode number, polarization, wavelength and waveguide width. The mode number ν is a discrete parameter, so all modes can be evaluated separately. The same holds for the polarization, because it is assumed that all modes are either quasi TE or quasi TM polarized. Therefore, the propagation constant only depends on two continuous variables: the wavelength λ and waveguide width W . In practice we can assign upper and lower values to both. These boundaries for λ and W also determine the maximum number of guided modes.

Within these boundaries a set of points is determined, for which values for the propagation constant β are calculated using a rigorous method. Afterwards, a model is fitted to the calculation results in order to obtain a continuous function over λ and W . A model can be derived using the concept of effective waveguide width W_{eff} . The effective width of a dielectric waveguide equals the geometrical width of an equivalent metallic waveguide [6]. The propagation constant can be expressed in W_{eff} :

$$\beta = \sqrt{\left(\frac{2\pi n_r}{\lambda}\right)^2 - \left(\frac{(\nu+1)\pi}{W_{\text{eff}}}\right)^2} \quad (1)$$

$$W_{\text{eff}} \approx W + \pi^{-1}(n_c/n_r)^{2\sigma}(n_r^2 - n_c^2)^{-1/2}\lambda \quad (2)$$

with n_r the ridge index, n_c the cladding index and $\sigma = 1$ for TE and $\sigma = 0$ for TM.

Combining equation (1) and (2) and introducing fit parameters C_i , we derive equation (3).

$$\hat{\beta} = \sqrt{\left(\frac{2\pi}{\lambda}(C_0\lambda^2 + C_1\lambda + C_2)\right)^2 - \left(\frac{C_3}{W + C_4\lambda}\right)^2} \quad (3)$$

Least squares fitting is used to determine the values of the model coefficients C_i that minimize the error $|\beta - \hat{\beta}|$. For least squares fitting to work, a good start estimate for the model parameters is necessary. The start values for C_0 , C_1 and C_2 are the parameters of a polynomial fit of the slab index. For C_3 the start value equals $(\nu+1)\pi$. For C_4 the start value is obtained as $\pi^{-1}(n_c/n_r)^{2\sigma}(n_r^2 - n_c^2)^{-1/2}$.

Testing the method

The described fitting method was applied to a high-index contrast InP ridge waveguide. First an effective index method was applied. The obtained ridge index was fitted versus wavelength with a second order polynomial. For strongly dispersive layer stacks a higher order polynomial may be needed. The cladding index was fixed at 1.0.

The propagation constant β was calculated for $\nu \leq 20$, $1.5\mu\text{m} \leq \lambda \leq 1.6\mu\text{m}$ and $1.0\mu\text{m} \leq W \leq 20\mu\text{m}$ for TE and TM. The sampling points form a rectangular grid of 11×191 over wavelength and waveguide width respectively. A 1D mode solver was used to be able

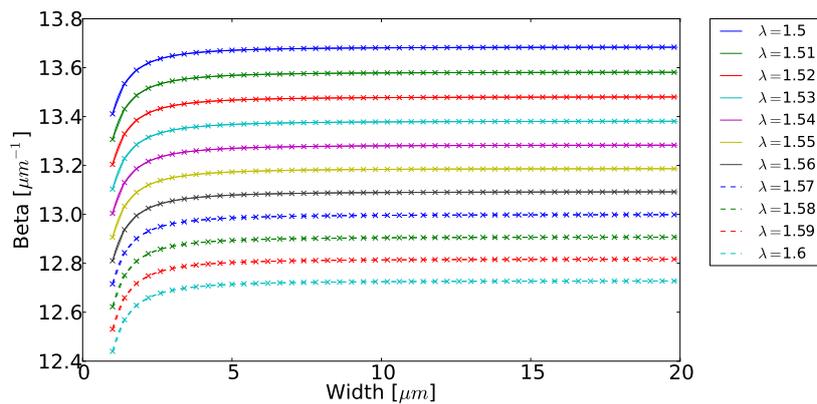


Fig. 3: Rigorously calculated β (crosses) and fitted $\hat{\beta}$ (lines) versus waveguide width, and wavelength as a parameter.

to quickly recalculate the data set, but 2D mode solvers can also be used without any adaptation of the fitting method. Fig. 3 shows the sampled values and the fit function with wavelength as a parameter. After obtaining the fit coefficients, the coefficient of determination R^2 can be calculated as $1 - (\sum (\beta - \hat{\beta})^2) / (\sum (\beta - \bar{\beta})^2)$, with $\bar{\beta}$ the mean of the calculated propagation constants. For a perfect fit R^2 equals 1. Out of all considered modes and polarizations, the worst fit had an R^2 equal to 0.9999966. This indicates that the model of equation (3) is well suited to describe the data.

Conclusion

From a designer point of view the required features of a photonic component library were described. Also a fast way of determining the propagation constant in waveguides was proposed. This method offers high simulation speeds and inherent numerical stability at the cost of decreased flexibility and slightly decreased accuracy. In a generic foundry approach the technology is already fixed, resulting in no loss of flexibility at all. This leads us to conclude that the method is well suited for circuit level simulation.

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