CAPHE: a circuit-level time-domain and frequency-domain modeling tool for nonlinear optical components

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We present CAPHE, an optical circuit modeling tool that can be used both in frequency and in time domain. The tool is based on the definition of a node, which can have both an instantaneous input-output relation, as well as different state variables (such as temperature, carrier density...) and differential equations for these states. Furthermore, each node has access to its input at all previous timesteps, allowing to create delay lines or digital filters. A node can contain sub-nodes, allowing to create hierarchical networks. This tool is useful in numerous applications: frequency-domain analysis of optical ring filters, time-domain analysis of optical amplifiers, microdisks, nonlinear resonators...

Introduction

There are a lot of methods for modeling optical components, such as Finite Difference Time Domain (FDTD) (e.g. MEEP [1, 2]), eigenmode expansion, Time Domain Traveling Wave (TDTW) [3], Coupled Mode Theory (CMT), the Modified Nodal Analysis (MNA) (see e.g. OptiSPICE [4])... The major difference between these tools is the level of physical detail they contain. FDTD, for example, is directly based on Maxwell's equations and therefore computationally very expensive. CMT, on the other hand, is an approximate description, but extremely fast: one only needs a few variables to describe the whole system.

In this paper, we present a tool that is capable of modeling systems both in time and in frequency domain. In the time domain it is based on CMT. It is proven that for certain coupled resonators, CMT is very accurate compared to FDTD [5], so our framework can model these systems with reasonable accuracy and within reasonable time. Also, using the frequency domain techniques, we can eliminate passive linear components before the time-domain simulation begins, again decreasing the simulation time. Furthermore, each component can be represented in a natural way using variables like optical field, temperature, carrier density... without needing to be mapped on to voltage or current such as in the MNA approach.

Our tool, named CAPHE [6] can also be used to simulate novel computational systems such as photonic reservoirs [7]. It is written in C++ for optimal performance, with a Python front-end for ease of use and interfacing to a large collection of scientific libraries.

In the next section we define a node according to the framework. After that we show how an optical signal is represented, and we explain the rationale behind the elimination of linear components. Finally we show two examples, one in frequency domain and one in time domain.

Node model

A node consists of N ports, see Fig. 1. A linear instantaneous transmission between port $s_{in,i}$ and $s_{out,j}$ is defined through the scatter matrix $\mathbf{S}_{ij}$. Two optional time-domain

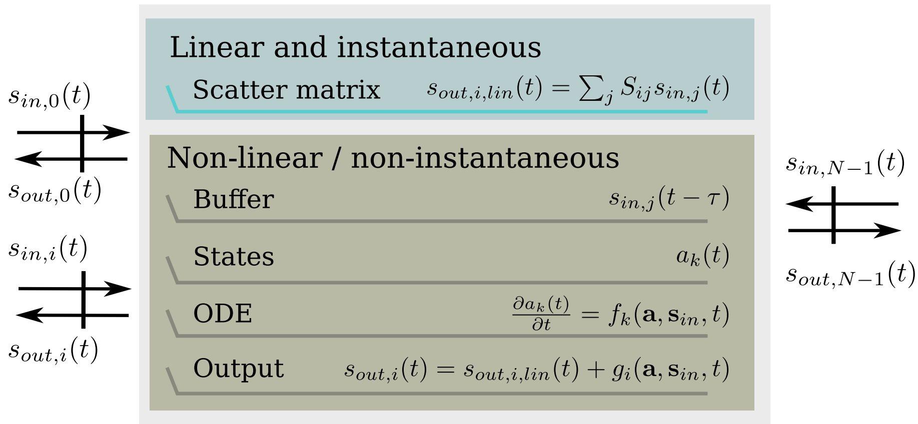


Figure 1: A node has N input/outputs and can be linear or nonlinear. See text for details.

descriptions can be added to enrich this component (see Fig. 1, bottom): First, one can add a *buffer* to store the inputs $s_{in,i}$ at previous timesteps. This can be used if one wishes to model a delayed waveguide or a digital filter. Second, we can add internal *states* to the node. This can be used to describe the rate equations of, e.g., a laser or the complex amplitude of a resonator. We use a set of ordinary differential equations (*ODE*) to describe the component in terms of its internal variables. There is no restriction on the form of the equations, so highly nonlinear components can be easily modeled. With these two additions, the *output* $s_{out,i}$ is now a sum of the linear part and a term describing the nonlinear character of the component.

Representation of an optical signal

We represent time signals as complex amplitudes $s(t)$, modulating a carrier frequency ω_c. The actual input at each port is then

$$E(t) = s(t)e^{j\omega_c t} + c.c. \tag{1}$$

Representing the signal by $s(t)$ rather than by $E(t)$ is beneficial from a numerical point of view, as we can now integrate over $s(t)$ which varies much slower than $E(t)$. Obviously, as the bandwidth of the input signal increases, we will need more samples per time unit to correctly simulate the system.

Differential equations can be added to describe the evolution of some variables, e.g., temperature and free carriers in a laser as a function of time and inputs.

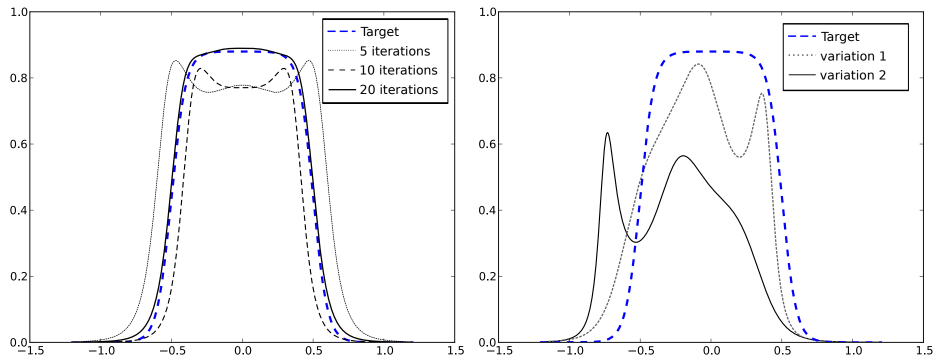
As soon as a differential equation is added, or the output is dependent on previous inputs, the component is not instantaneous anymore. We call these nodes memory-containing (MC) nodes (Fig. 1, bottom), as opposed to the the memoryless (ML) nodes.

Scatter matrices

A scatter matrix is defined for each node (see Fig. 1), but also for each (sub)circuit. In a circuit, this matrix describes the total transmission from and to all ports in the network. This matrix can become big if the number of components is large, and hence slow down the time-domain simulation. For this reason we derived techniques to eliminate the ML nodes. The resulting scatter matrix is then smaller. The elimination involves solving sparse matrix systems, which can be done very efficiently using KLU [8].

Example 1 - CROW (Coupled Resonator Optical Waveguide)

In this first example, we show how to design a CROW, which is a sequence of optical rings. By adjusting the coupling strengths κ_i of the coupling sections, we can design filters with a desired shape, such as a flat band filter with a certain wavelength range. The target filter has a transmission which is flat over 1 nm (see Fig. 2(a)). Here we choose a small network of only four rings for demonstration purposes.



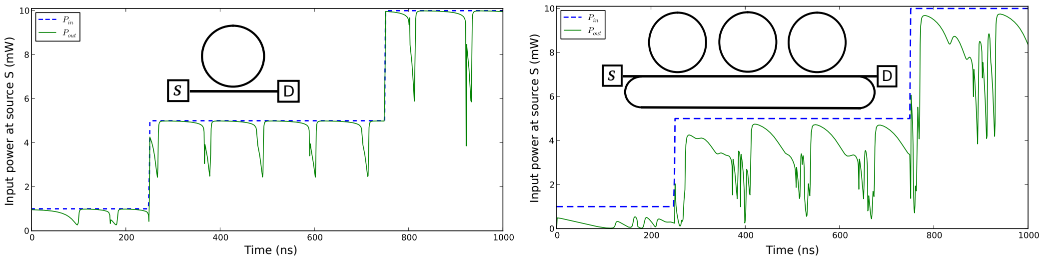
(a) Optimizing the filter (b) Process variations

Figure 2: CROW: Designing a flat-band filter by optimizing the coupling strengths (left). With process variations, performance deteriorates (right).

To find a set of κ_i, we use an evolutionary algorithm to optimize the coupling coefficients κ_i for $i \in [1,5]$. Each simulation takes about 200 *ms*. After 33 generations with a population size of 14, we get a solution that is close to the desired function, see Fig. 2.
We can compensate for the process variations by changing the refractive index locally using micro-heaters on top of the waveguides. Suppose the ring resonances due to process variations can vary over 1 nm [9], then, after further calculations, this leads to a power budget of approximately 3 mW to thermally tune the rings to match the filter.

Example 2 - Dynamics of coupled ring resonators in a feedback loop

In the second example we demonstrate the dynamics of a ring resonator. The microring is represented by four dynamical variables: two complex amplitudes for the energy and phase of the light travelling in the CW and CCW direction, the temperature, and the amount of free carriers. This system contains a lot of different timescales: the temperature time constant (approx. 100 *ns* - 1 μs), the free carier relaxation time (approx. 1-10 *ns*), the coupling between the ring and the bus waveguide (approx. 10-100 *ps*) and the coupling between the CW and CCW mode (can be faster than the nanoseconds timescale).



(a) Self-pulsation in a single (all-pass) microring

(b) Dynamics of a system with three (all-pass) microrings coupled with a feedback loop

Figure 3: Time-domain simulations

Given the different timescales and the compact formulation of the basic equations, our tool is very well suited to simulate this system. In Fig. 3(a) we show how different fixed input powers can trigger the experimentally observed self-pulsation in an all-pass filter. In Fig. 3(b) we investigate a system of three coupled self-pulsating microrings with an external feedback loop.

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