'Aurora' - a time domain based meta-algorithm for the rapid simulation and design of complex optical circuits.

E.J. Klein, R. Dekker and A. Driessen.

MESA+ Institute for Nanotechnology, Integrated Optical Micro Systems, University of Twente, Faculty of Electrical Engineering, Mathematics and Computer Science, P.O.Box 217, 7500 AE Enschede, The Netherlands. Phone: +31-53-489 4449; E-mail: E.J.Klein@utwente.nl.

A new simulation tool called 'Aurora', specifically developed to efficiently simulate highly complex optical devices such as OADMs and Routers based on (higher order) microring resonators, is presented. The meta-simulation algorithm used by Aurora creates a framework in which many different simulation algorithms can be properly combined rather than providing a simulation algorithm itself. The calculations of this program use a simple scheme based in the time domain from which the frequency response can easily be derived. Simulation results of a 4-port OADM and waveguide gratings show excellent agreement when compared to experimentally obtained measurement data and conventional simulation methods.

Introduction

Due to market demands for more device functionality and the desire to reduce cost, an increasing number of optical functions is miniaturized and integrated onto a single chip. Often this new functionality is realized using resonant structures such as microring resonators, gratings or photonic crystals that allow for a large functionality to be realized on a small footprint. In theory the behavior of such complex devices that consist of many (resonant) subcomponents can be simulated numerically using simulators that employ electro-magnetic (EM) wave propagation methods. In practice, however, using EM based methods for these devices is highly time consuming due to the fact that the area to be simulated is generally large and the fact that the inclusion of resonant structures requires more complex algorithms or significantly longer simulation runs.

A more efficient method to simulate these devices can be found by taking a circuit level approach to the component. Similar to design methods used in electronic engineering this approach assumes that a complex optical device such an OADM or a less complex microring-resonator can be reduced into a combination of basic optical "constructs" such as for instance waveguides or couplers. This allows the contents of each construct to be calculated individually, as long as the results of the individual calculations are properly forwarded between the constructs to ensure that their combined behavior is identical to that of the original component. The simulation engine of the 'Aurora' tool discussed in this paper is based on this assumption.

Simulation method

Usually a simulation method refers to the type of algorithm that is used to perform the simulation (e.g. BPM, FDTD or Transfer Matrix). However, the simulation method of Aurora does not use any specific algorithm but leaves it up to the individual optical constructs to provide their own simulation algorithms. The simulation method can therefore be classified as a meta-algorithm that creates a framework in which many different simulation algorithms can be properly combined rather than providing a

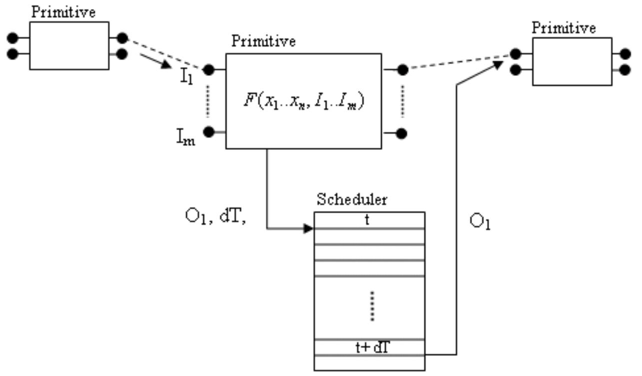

Figure 1. The simulation method used in Aurora: the results from the calculation in one primitive is sent to a scheduler which forwards these results to a connected primitive after a certain delay dT. This delay represents the propagation time of light through a waveguide and is required for a correct simulation of an optical component.

simulation algorithm itself. It is then these algorithms that together act as a single (but distributed) algorithm that can be used to simulate the component.

In the simulation the basic optical constructs such as waveguides, couplers, gratings, tapers etc. are represented by 'primitives'. A primitive contains the required equations or simulation method to accurately represent the optical construct and has a certain number of inputs 'I' and outputs 'O' representing the in-and outputs of the construct. In order to simulate the time delay associated with an optical signal that travels a certain distance through a waveguide a time delay is taken into account between the instant that a signal enters one of the inputs I_i and the moment when the results of the calculation within a can be forwarded to the next primitive. Instead of directly forwarding the results from the calculation in one primitive to the next primitive the result is in stead redirected through a scheduler as shown in Fig. 1. This scheduler will then ensure that at the correct time the result data belonging to output O_i is placed on the port connected to this output.

Simulation results – waveguide grating

For an accurate simulation of a waveguide grating in 2D or 3D, EM based methods such as FDTD, or Bi-directional Eigenmode Propagation (BEP) can be used. These methods provide an accurate simulation of the grating in the time- as well as the frequency domain but are computationally intensive and therefore slow. If the grating consists of a shallow etched waveguide, however, the propagating modes are weakly confined which allows the grating to be approximated by a 1D Bragg stack. This approximation replaces the alternating sections in the waveguide grating with a film that has a refractive index $\tilde{n}_i$ and thickness d_i equivalent to the respective effective refractive index N_i and length L_i of that section (see Fig. 2).

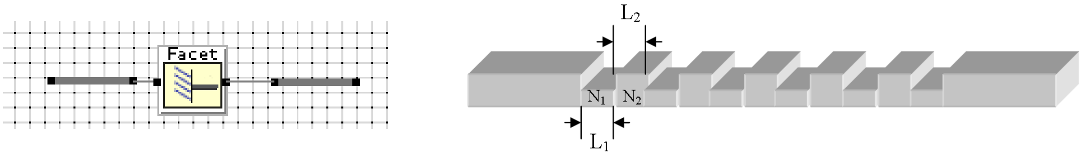

Figure 2. The implementation of a single grating period in Aurora.

The transmission, reflection and absorption of such a 1D Bragg stack can be calculated using the transfer matrix method but does not allow time domain evaluation. Alternatively, the grating can also be implemented using Aurora. Although the simulation of a grating in Aurora cannot calculate as fast as a transfer matrix method, it allows time domain simulations and will outperform more rigorous simulation methods such as FDTD and BEP in calculation time. In Fig. 3 shows an Aurora implementation of an 11 period grating with a period length Λ of 2 μm and a duty cycle of 50%. The indices of the grating periods were set at 1.5 and 3. These values are not in accordance with the condition of weak confinement that allows 1D simplification but are used for illustrative purposes.

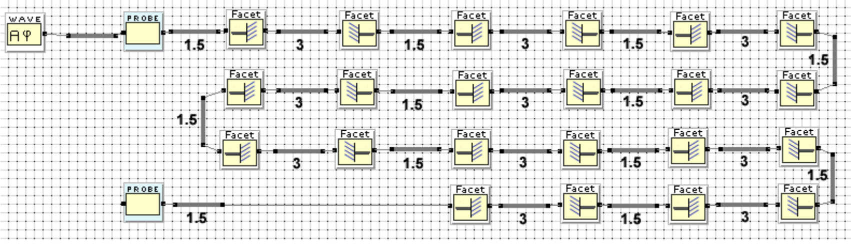

Figure 3. Implementation of an eleven period grating in Aurora.

The simulations in Aurora of this particular grating (across 400 wavelength points) took 18 seconds to calculate on an Athlon 3000+ CPU. While this is several orders of magnitude slower than the Transfer Matrix method, it is still fast in comparison with the EM based methods. The overlap between the reflection spectra is near perfect as can be seen in Fig. 4.

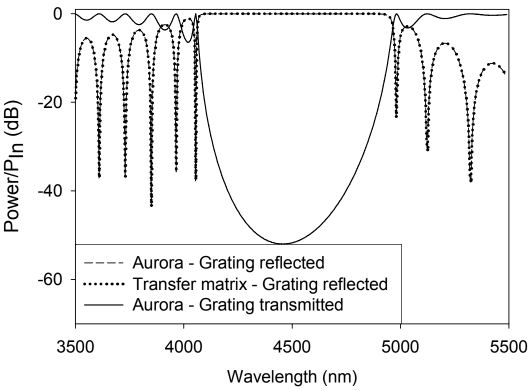

Figure 4. Grating transmission and reflection as a function of the wavelength. The simulated reflection spectra calculated with Aurora and SimuLayer lie perfectly on top of each other.

The real advantage of Aurora, however, is in the simulation of the time-domain step responses of which the results are given in Fig. 5. The left plot shows the step responses of the transmitted and reflected light at the second maximum in the transmission, located just below the bandgap of the grating at a wavelength of 3965 nm. The responses do not begin at $T = 0$ due to the length of the input waveguide, resulting in a delay of the signals by ≈1.5 ps. Figure 5 shows the responses calculated for the center of the bandgap, at 4455 nm. Clearly, the interaction of the light within the grating at this wavelength is much more complex than the interaction at a wavelength of 3965 nm, as can be concluded from the many oscillations in this figure.

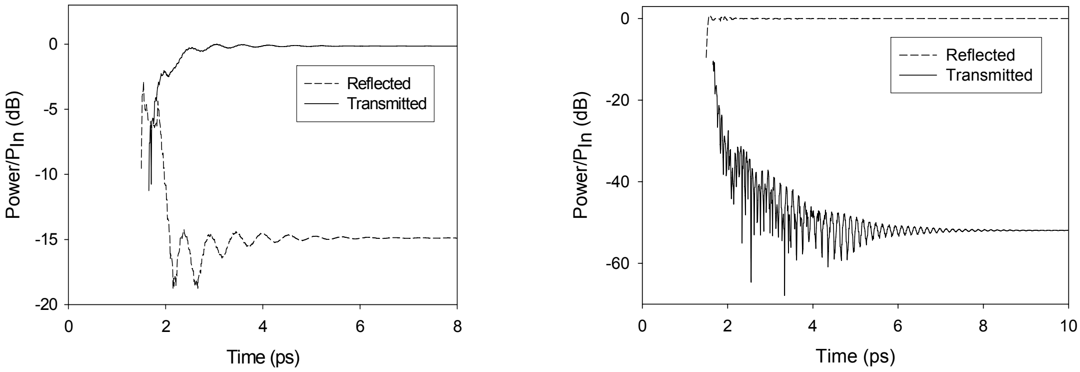

Figure 5. (Left) Step responses of the transmitted and reflected light outside the bandgap at 3965 nm and (right) in the middle of the bandgap at 4455 nm.

Simulation results – Optical Add Drop Multiplexer

A microring based OADM designed for operation at 1300 nm, of which a microscope image is shown in Fig. 6, was measured using a broadband source and an optical spectrum analyzer with a resolution of 0.05 nm. The left plot in Fig. 7 shows the normalized drop responses measured when the broadband source was connected to the "In" port of the OADM. The resonance frequency of each resonator has been tuned to a different wavelength to demonstrate the dropping of four different channels. In the drop responses of the resonators the individual effects of the adjacent MRs can be observed, for instance in the response at the fourth drop port. The three dips in the response of this port are the through responses of the three preceding resonators. With the known parameters of $\kappa_1=\kappa_2=0.40 \pm 0.01$ and $\alpha_{dB}=33 \pm 3$ dB/cm a simulation of the OADM was created in Aurora. The results from this simulation are given in the right plot of Fig. 7. As can be seen, the measured and simulated responses look very similar, showing the applicability of Aurora as an optical circuit simulation tool.

Figure 6. (Left) Microscope image of fabricated OADM. (Right) Implementation in Aurora.

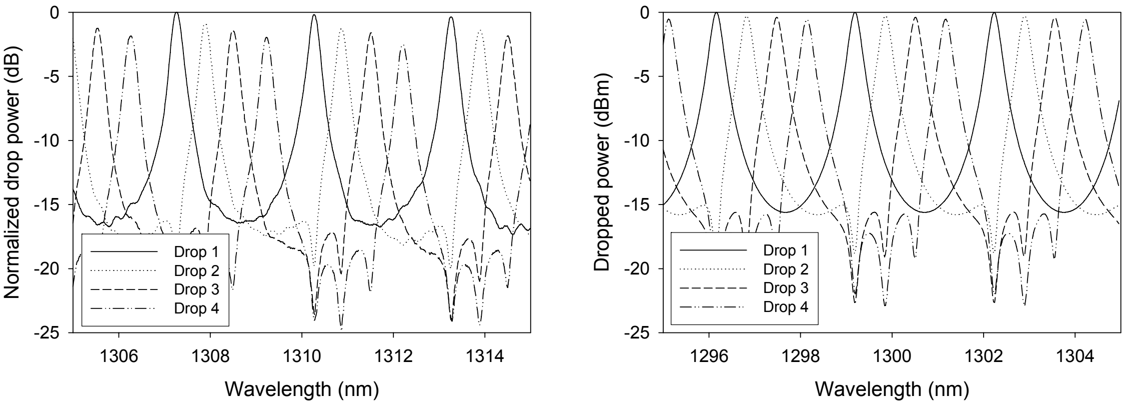

Figure 7. (Left) Experimentally observed and (right) simulated drop responses of the OADM.

Conclusions

We have shown a new simulation tool called 'Aurora' which uses a simple but effective simulation method for simulation complex optical circuits the frequency as well as the time domain. Simulations on certain classes of waveguide gratings can be performed orders of magnitude faster than conventional EM based methods whilst retaining the ability to look at time domain responses. Comparisons between measured data and simulations have shown that Aurora can be used for predicting the behavior of complex optical components.