S-matrix oriented simulation of a looped-back four channel add-drop multiplexer

S-MATRIX ORIENTED SIMULATION OF A LOOPED-BACK FOUR CHANNEL ADD-DROP MULTIPLEXER

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Abstract

A design tool for simulation of complex photonic integrated circuits is described. An example simulation of a four-channel add-drop multiplexer is presented and results are in good agreement with measurements.

Introduction

Computer aided design (CAD) tools for photonic integrated circuits generally initiate the design and simulation based on a layout description of the circuit and use BPM techniques to carry out the simulation. We have chosen to use a more flexible approach initiating the design on a symbolic level and performing the simulation and the generation of the mask layout from that level. The advantage of this approach is that the circuit is better structured and that both BPM and other simulation methods can be implemented for different components or sub circuits. We have chosen to base our CAD-tool on a professional microwave design system (Hewlett Packard's MDS) in which we have implemented optical component models for handling propagation and coupling of optical fields [1].

Description of optical components

The coupling between optical components takes place via guided modes and radiation fields. If coupling through radiation fields is small, optical components can be considered as individual units connected to each other at well defined ports. In this concept, the response of an N-port component is described by its $N \times N$ S-matrix.

An ideal mono-mode waveguide is a 2-port component. The propagation in a straight waveguide is described by $S_{12} = S_{21} = e^{-j\beta\ell}$, with β the propagation constant and ℓ the length of the waveguide. For a curved waveguide $S_{12} = S_{21} = e^{-j\beta_\phi\phi}$, with β_ϕ the angular propagation constant and ϕ the angle of the curved waveguide. Since there are no reflections in the waveguide, $S_{11} = S_{22} = 0$.

In order to obtain the S matrix, any mode solver calculating the modal propagation constants can be used. The current implementation offers the choice of the effective index method, in combination with a conformal transformation for curved waveguides [2], and a 2D finite element method. A beam propagation method is used for components where coupling through radiation fields plays an important role.

The junction between two mono-mode waveguides is described by a 2×2 scattering matrix. The matrix elements are given by the overlap integral of the modal fields U_1 and U_2 in each of the waveguides: $S_{12}^* = S_{21} = \int U_1 U_2^*$. As reflections in optical chips are small for many applications, S_{11} and S_{22} are set to zero, although inclusion of reflections is straightforward.

Simulation of phased array demultiplexer

The simulation of a phased array demultiplexer (PHASAR) is performed in two steps. First the geometry of the PHASAR is created with the desired specifications, such as the number of input and

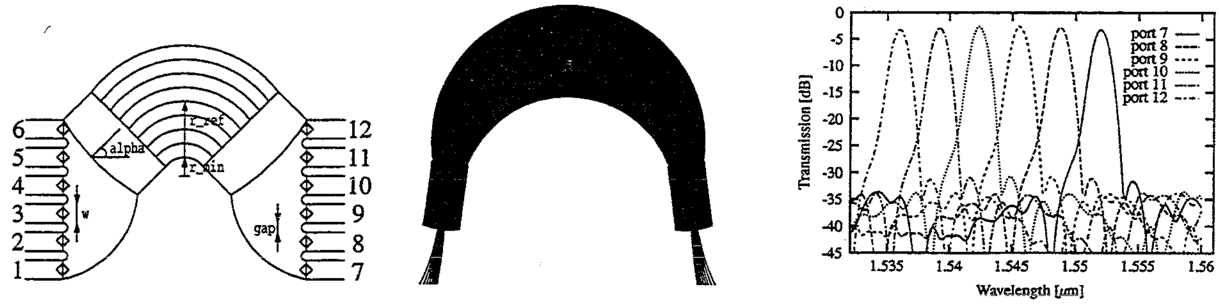

Figure 1: Symbolic representation of a 6×6 PHASAR and the layout generated by this component for the ADM application. The wavelength response of the PHASAR is shown with the signal launched in input 1.

output ports, the central wavelength and the channel spacing. Secondly, the propagation through this PHASAR is simulated.

The design of the PHASAR geometry is based on the description by Smit [3] and uses two star couplers connected by an array of straight and curved waveguides. A PHASAR with N input and M output waveguides is described by an $(N+M) \times (N+M)$ S-matrix. The matrix elements S_{ij} are calculated in the following way: first the field from port i is diffracted using the Rayleigh-Sommerfeld model [4] and the coupling coefficient with each waveguide of the array is calculated. These coefficients are corrected for coupling between adjacent array waveguides by a normalisation procedure using the super modes of the waveguide array, which are constructed following the description by Chiang [5]. Secondly, the propagation in each waveguide is calculated taking into account the coupling loss at the junctions and the radiation loss in the curved waveguides. As an option, the phase transfer of each waveguide in the array can be changed randomly by a small amount with a normal distribution, in order to simulate the phase incoherence in the array due to imperfections in the fabrication process. Finally, the coupling coefficient between each array waveguide and the diffracted field of output port j is calculated using the same method as for the input ports.

An example of the symbolic representation in MDS of a 6×6 phased array together with the mask layout and the simulated response is shown in figure 1. This PHASAR has a free spectral range of 40 nm and a channel spacing of 400 GHz (3.2 nm). The simulated loss of the PHASAR is between 2.5 dB and 3.2 dB and a phase noise with a width $\sigma_{\Delta\varphi} = 8°$ was chosen to match the measured crosstalk level.

Simulation of a 4-channel add-drop multiplexer

As a next step we simulated a four channel add-drop multiplexer ADM. The ADM consists of a 6×6 PHASAR (de)multiplexer in loop-back configuration, as reported by Vreeburg [6]. The loop-back paths contain Mach-Zehnder interferometric switches [7] composed of straight and curved waveguides and two 3 dB MMI couplers [8]. The switches are used to open and close the loops. The symbolic representation of the circuit in MDS is shown in figure 2.

Four wavelengths ($\lambda_1 \ldots \lambda_4$) from the input waveguide are demultiplexed by the PHASAR and are routed to the switches (S1...S4). Each wavelength can be switched to the drop ports (D1...D4) or back to the PHASAR where the signals are multiplexed into one output waveguide. If a signal is routed to the drop port then another signal of the same wavelength can be added at the proper add input (A1...A4) and will be multiplexed to the output waveguide.

The simulated response[1] of the ADM, with all signals looped back to the PHASAR is shown in figure 3(a). Four peaks are visible ($\lambda_1 \ldots \lambda_4$) and a fifth peak originating from the direct signal from

[1] All simulations have been performed for TE polarisation.

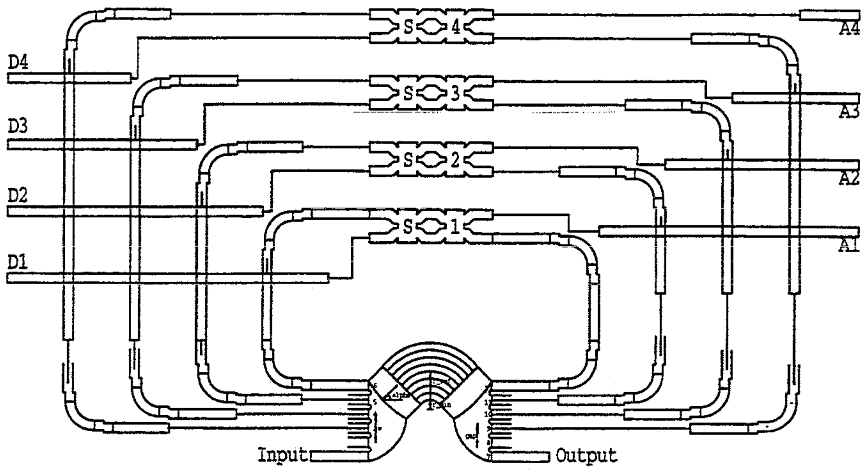

Figure 2: Symbolic representation of the four channel ADM circuit.

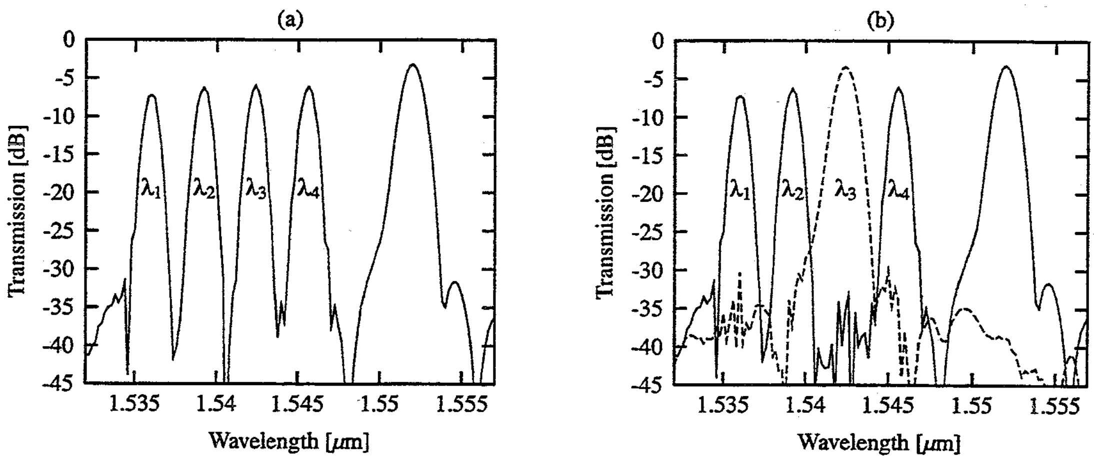

Figure 3: Simulation results of a four channel ADM. (a) Response at the output of the ADM. All switches are in the cross state. (b) Signal at the output of the ADM with switch 3 in the bar state. The added signal is shown with a dashed line.

input to output. The simulated loss of the ADM is between 5.9 dB and 7.2 dB.
The simulated response of the ADM when switch 3 is active is presented in figure 3(b). The signal passing switch 3 is routed to the DROP port. At the output port, only three channels are present. However, a signal at λ_3 has been added at the A3 port (dashed curve in the figure). The peak at this wavelength has a larger width and exhibits a lower loss because the signal traverses the PHASAR only once.

Comparison with measurements

An InP-based four-channel ADM with a design identical to the simulated ADM was realized by Vreeburg [6]. The measured responses are presented in figure 4 for all switches in the cross-state (a) and for only switch 3 in the bar state (b). A comparison between simulation and measurement shows a shift in wavelength of $\Delta\lambda = 9$ nm. This is mostly due to a difference between the designed and the fabricated waveguide structure. The measured losses are between 7 dB and 9.1 dB. The simulated losses are less (5.9–7.2 dB) but the simulation does not take into account the loss due to the propagation in the waveguides which was measured to be 1.5 dB/cm. Since the length of the loop is aproximately 1.2 cm this accounts for the difference. The simulated loss of the waveguide crossings is 0.1 dB per crossing. The measured value is 0.3 dB per crossing. This accounts for the

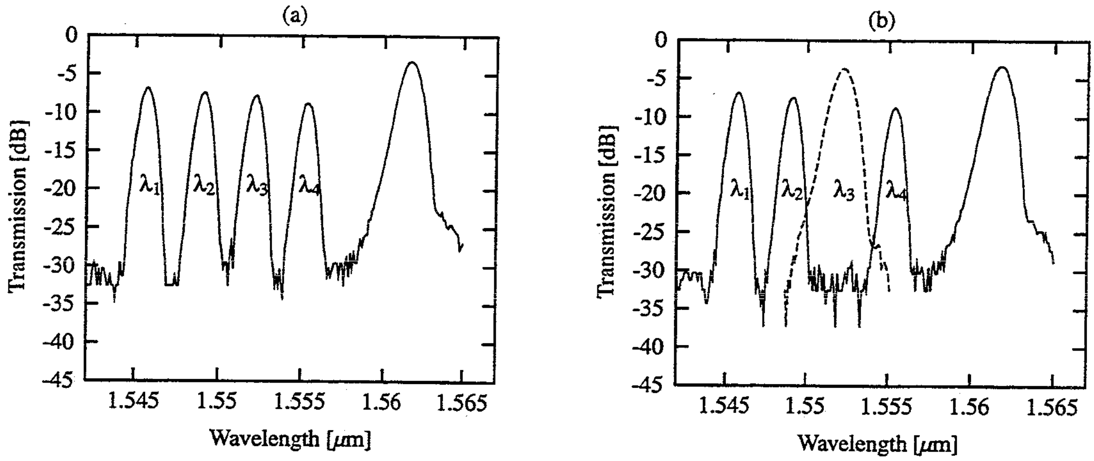

Figure 4: Measurement results of a four channel ADM. (a) Response at the output of the ADM. All switches are in the cross state. (b) Signal at the output of the ADM when switch 3 is in the bar state. The added signal is shown with a dashed line.

difference in relative peak height since the signals at λ_1, λ_2, λ_3 and λ_4, pass 1, 3, 5 and 7 crossings, respectively. Figure 4(b) shows a residual signal for λ_3 about 30 dB below the original signal. This is in good agreement with the simulated value. The origin of this residual signal is the extinction ratio of the switch and the phase errors of the PHASAR.

Conclusion

An example of an application of a powerful CAD-tool for photonic integrated circuits has been presented. The *S*-matrix approach enables the simulation of complex circuits, including loops, such as the one analysed in this article. Comparison with measurement demonstrates the validity of the simulations.

Acknowledgement

Part of this work was carried out in the ACTS-BLISS AC-065 project. The support of CNET LAB/FCI/PIH is also acknowledged.

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