Design of photonic components

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Abstract

Since the 60's integrated optics has been forecasted a promising future. Almost thirty years after photonic components were first proposed, their usage in actual products is still very low. However, this will change as steadily increasing bandwidth needs ask for optical transparency in the networks. This development is accompanied by increasing demands for design and modelling tools. This paper gives an overview of tools used in photonic components design.

Introduction

There are two developments that are largely changing the face op optical tele-communication. One is optical amplification; Erbium Doped Fibre Amplifiers (EDFA) and, to a lesser extent, Semiconductor Optical Amplifiers (SOA) are now commercially available and paving the road for repeaterless, optical transparent, fibre communication. The other development is Wavelength Division Multiplexing (WDM). In this scheme multiple wavelengths are used to simultaneously transport (and route) large amounts of data over fibre. The combination of the two is expected to deliver affordable solutions for high bandwidth demands at low prices, potentially through upgrades of installed fibre-links. As a side effect the research on and development of photonic components, notably wavelength (de-) multiplexers and optical transparent switches, is increasing. This is reflected by a growing demand for design and modelling tools. Since developing such tools is time-consuming and expensive, and since the requirements that these tools have to meet are high, commercial software is increasingly finding its way towards customers [1].

The design trajectory

In order to make an inventory of the required design tools for photonic components one has to know what the design process looks like. Figure 1 shows an attempt to generically describe design processes [2]. It depicts various phases of a highly iterative design process as well as the required CAD tools. Ideally the process starts from a clear few of the optical functionality that has to be implemented as well as the associated fundamental requirements (1). The modelling in (2) is preferably analytical and serves to elucidate the basic device principle. In this phase models are build on an adhoc basis and may lack generality. Perturbation theory (e.g. Coupled Mode Analysis, CMA) can be used as a starting point. In (3) more general simulation tools, which are preferably not based on the assumptions made in (2), are used to get insight into higher order and potentially detrimental effects. In this phase one needs powerful and accurate numerical tools such as Finite Difference (FD) or Finite Element (FE) mode-solvers, Beam Propagation Method (BPM) and Eigen-mode Propagation (EP) techniques. In this phase the design is optimised resulting in a set of requirements to be matched by the materials and fabrication technologies. In (4) the actual design is implemented meaning that one has to account for the specific material properties and technological imperfections. In this phase the complete lay-out of the photolithographical masks for wafer scale fabrication is carried out. Therefore, in (4) one needs design tools that can cope with the complexity of photonic components e.g. designs with several layers (one easily needs 5-10 masks for more complex devices). Desirably the tools in (3) and (4) are the same or at least compatible. This way it is easy to come from single models, collected in libraries enabling modular design, to entire wafer lay-outs. Design checking (5) can be performed both by simulation of the performance of the components as well as by comparing the mask lay-out against specific design rules (design rule checking). After this step the actual masks are produced and the components can be fabricated. In a next iteration the performance of tested devices is used to enhance the performance and/or tolerances of the design.

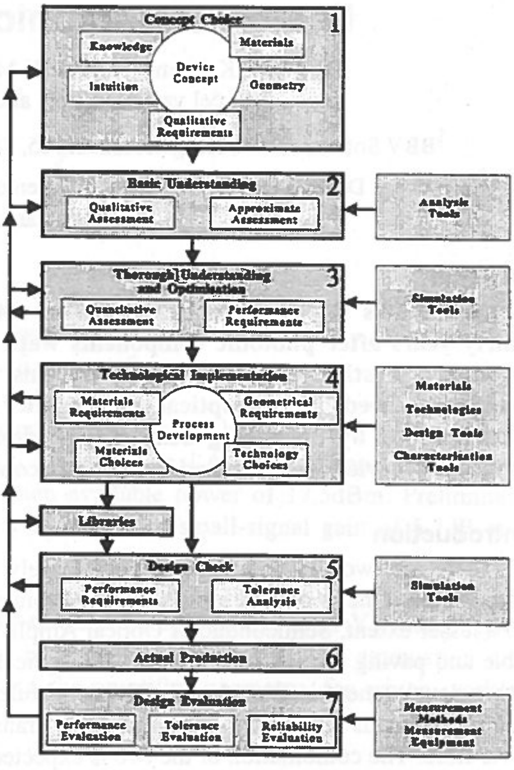

Figure 1: Schematic representation of the design process

Modelling tools

Various levels of modelling can be distinguished in design processes. From a bottom up approach one starts with the *physical modelling*. In the simplest case only the refractive indexes of materials are needed. More complex situations arise when e.g. materials with absorption, gain, nonlinearities, acousto-, thermo-, electro-optic, opto-electronic effects and the like are involved in the design. Within the context of photonic component design a general approach is to model these effects on sub-wavelength resolution and incorporate the material interaction in the numerical modelling. For (quasi-) static situations the resulting problems can often be solved by perturbation (e.g. thermo- or electro-optic modulation), iteration (e.g. mode solving with Kerr-nonlinearities), simulated diffusion (e.g. indiffused or bleached waveguides) or coupled equations (e.g. when dealing with second harmonic generation or gain material). Next to physical modelling *technology modelling* can account for the discrepancies between devices as designed and fabricated. This modelling can be used to either obtain more accurate simulations of the performance of the eventual devices (before they are fabricated) or to optimise the fabrication technologies in order to closely meet the design objectives. Examples of technology modelling are photolithographical, etch and deposition models. In its most basic form, technology modelling is found in waveguide width adjustments to correct for over-

	Design Phase				
Tool	**2**	**3**	**4**	**5**	**6**
Analytical	+				
Physical	+	+	+	+	+
Technological			+	+	+
Device		+	+	+	+
Design		+	+	+	+
Systems					+

Table 1: Modelling tools vs design phase

or under-etching. In the next step, *device modelling,* the device properties as well as the stimuli to which the devices will be exposed are used to simulate device performance. At this level there is a variety of commercial packages e.g. mode-solvers (1D, 2D, scalar, (semi-) vectorial), BPM software (2D, 3D, scalar, (semi-) vectorial), bend models, grating coupling models etc. More advanced modelling of e.g. travelling wave electrodes or generic temporal analysis of devices is still hard to find commercially although modelling methods have been described in literature (e.g. [3]). Finally the modelling chain is completed by *systems modelling*. In this type of modelling optical (sub-) functions are described by S-parameters or scatter matrices, generally representing characteristic in- and output quantities (e.g. eigen modes) of specific components. Complete systems are simulated by concatenating the scatter matrices of the individual functions. This type of modelling allows for symbolic design approaches albeit that the S-parameters generally have to be obtained using other methods (e.g. BPM or EP models) [4]. The various phases in the design trajectory can be combined with the distinct levels of modelling, giving a coarse idea of where the various modelling tools can be applied, as shown in table 1. Roughly speaking the modelling effort tends to increase with the design phase. Moreover, the quality of the modelling changes from analytically to numerically as more and more details are incorporated in the design.

Design tools

It may seem that powerful modelling tools suffice to design photonic components. This may be true for simple structures but for complex components dedicated photonic design tools are a prerequisite. Design packages can be classified in A) flat, B) hierarchical, C) parametric and D) symbolic tools. A) Flat design packages, which by now are obsolete, define all elements in absolute co-ordinates. B) Hierarchical packages allow for relative co-ordinates and models. C) Parametric packages add the use of expressions and dynamic connection of models. In analogy to the nodes used in electronic design tools, the implementation of parametric design at BBV uses *planes* to keep track of the mutual dependence of (sub-) models [1]. Figure 2 shows an example in which the connecting bends are changed; the design package automatically repositions the output sections in order to maintain the integrity of the design. Since parametric design is still lay-out oriented it allows for the incorporation of general simulation tools (e.g. BPM) albeit that these tools have restricted validity ranges (e.g. off-axis propagation is limited). D) Symbolic design is build on top of parametric design and adds the possibility to design by simply connecting objects on a graphical display [4]. Symbolic design is by far the most user-friendly approach. An implementation of symbolic design developed in the Netherlands by the Technical Universities of Delft and Twente and the Dutch PTT is based on a HP microwave design package. It uses (fast) scatter-matrix simulation with underlying EP, CMA, bend and BPM modules. There are four disadvantages of this approach: i) the scatter matrix method uses only eigenmodes and, thus neglects detrimental effects of radiation, ii) the geometrical data used in the calculations is not necessarily an exact copy of the real structure since the underlying models largely assume ideal elements, iii) all library models have to be modelled prior to use requiring programming of dedicated modules, iv) the approach does not allow for easy "upgrade" of simulation method (e.g. when you need 3D vectorial instead of 2D scalar calculations) unless all implemented models incorporate the required simulation capabilities. However, in practice these disadvantages can be circumvented by a judicious implementation of models and methods.

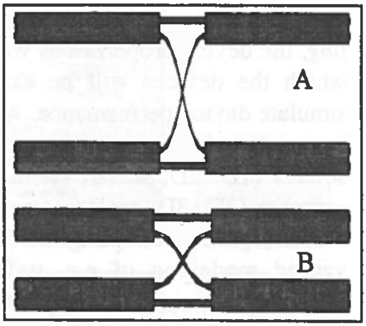

Figure 2: parametric design maintains design integrity.

The future of photonic design

In view of the advantages of symbolic design it can be expected that future design tools will largely be symbolic. To this end the disadvantages will be addressed, e.g. by internal (e.g. hidden to the user) fall-back to lay-out oriented approaches. It can also be expected that physical and technology modelling will be largely incorporated into the design tools in order to improve the designs and reduce the number of iterations required in the design processes. With continuously increasing computer power the device modelling will be enhanced by a gradual shift from 2D (1D) scalar to 3D (2D) vectorial simulations in order to account for polarisation dependence and polarisation conversion. In the long run mixed 3D spatial - temporal models will be implemented to model time-dependent processes. Apart from dedicated simulation tools it is to early to predict the future of general, commercial tools for mixed signal simulations such as required for laser modelling. With regard to design complexity future developments will show the integration of an increasing number of optical functions in combination with automatic routing and design rule checking, much in analogy with electronic design tools. In the long run tools for stacked waveguide layers (much like a modern PCB or IC-design) will be implemented. Ultimate design tools will be photonic hardware compilers, i.e. based on a description of the required performance and the available technology, device concepts will be automatically chosen and models will be automatically positioned. But this will certainly not be in the 20th century.

As the field of photonic design is maturing, there is a gradual shift from scientific to more development oriented work. Therefore, despite a natural resistance found under scientists, the shift from proprietary to commercial software tools will become increasingly complete.

Conclusions

Driven by current and future needs, photonic simulation and design tools are rapidly evolving. As much scientific theoretical work has already been done in the past thirty years, commercial packages will get steadily more powerful and proprietary programs will disappear in favour of, easy to use commercial integrated design environments.

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