Smart algorithms and smart design tools

Even though James Clerk Maxwell derived his famous set of equations around the year 1865, solving them to accurately predict the behaviour of light remains a challenge. In the design of photonic integrated circuits, which are used as chemical or biological sensors and as chips for fiber-optic communication systems, simulation of light on a micro-scale is of utmost importance. However, the complexity of modern devices is such that full, direct simulation is impossible – hence there is a need for smart algorithms and smart design tools.

• Remco Stoffer, Alyona Ivanova and Twan Korthorst •

In photonic integrated circuits, or PICs, functionality is created by manipulating light on a micro- or nanoscale. Light can be guided in small dielectric or semiconductor waveguides, much like in optical fibers. Light from a laser or from an optical fiber can be taken across the surface of an optical chip. This guidance and the interaction between waveguides provide passive functionality, and furthermore, the guides may be used to transport the light to parts of the chip where interaction with the outside world may take place. The two main areas of PIC application are sensors and telecommunications.

Since the interaction of light with substances on the surface of the optical chip is limited to a layer very close to the surface, minute quantities or very small concentrations of chemicals or biological antibodies can be accurately sensed by integrated optical sensors. Commercially available [1] sensors can measure down to a refractive index change of about 10^{-8}, which corresponds, for example, to a sugar concentration of only about 0.7 mg in a liter of water.

Data communication bandwidth needs are ever increasing, and ultra-high-bandwidth fiber-optic links are used in the backbone of the internet; moreover, more and more private homes get access to direct optical fiber links, the so-called ‘Fiber to the Home’ initiatives. PICs are employed at the transmitter and receiver end of these optical fibers. Traditionally, a PIC would be used to modulate the signal data, as supplied by an electronic circuit, onto the optical carrier. The potential data rate that a fiber-optic cable can transmit, however, is far higher than electronics can reach. The functionality of communication PICs has therefore been expanded to multiplex many different electronic signals into one optical signal – for example, by modulating each electronic signal at a different optical wavelength – and to include lasers and detectors. For examples of such PICs, see Figures 1 and 2.

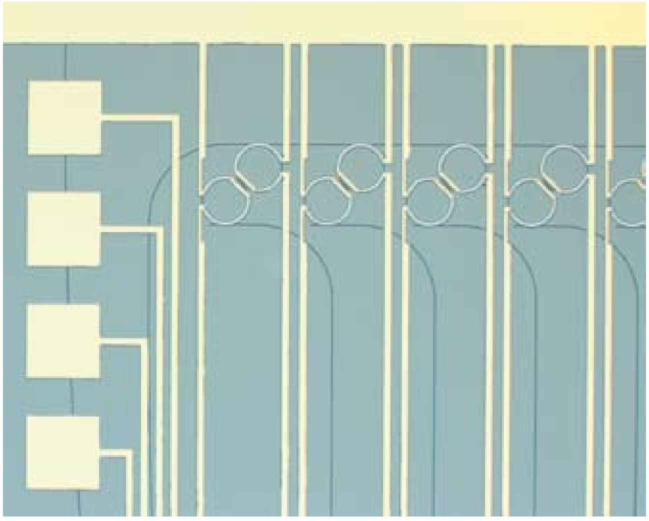

Figure 1. A photonic integrated circuit that dynamically routes signals at different wavelengths to different customers. Waveguide widths are typically in the order of 2 µm [2].

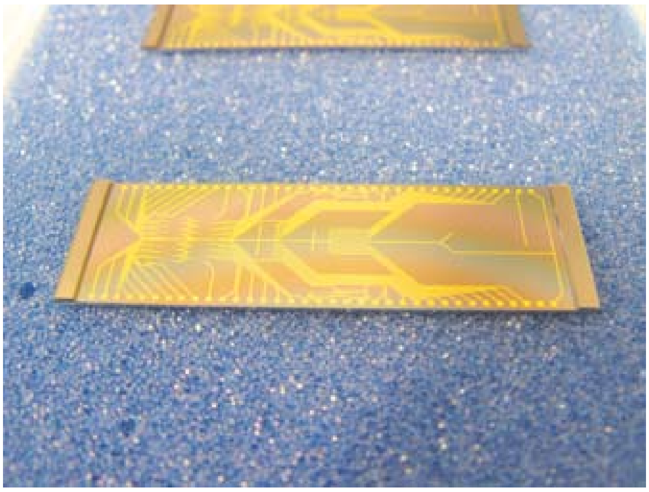

Figure 2. Athena, an integrated chip combining filters, splitters and switches [2] [3].

PIC Design

As the industry is maturing, the specifications of devices get tighter and tighter. Because of this, it becomes ever more important to have good control over and knowledge about the fabrication processes of the chips. Process flows and measured data are stored in databases, such as PhoeniX Software's manufacturing execution system, the 'Living Database' [4]. From such a system, fabrication variations can be obtained; for the various steps in a process, the standard deviations of the results become known.

In the design of photonic devices, simulation of the behaviour of light is of crucial importance. Over time, many different calculation methods have been created, starting from mode solvers of one-dimensional planar waveguides and two-dimension unidirectional beam propagation methods (BPM, see Figure 3) and culminating in advanced full 3D vectorial calculation methods like 2D mode solvers [4] (see Figure 4), 3D BPM [4] or Finite Difference Time Domain (FDTD) [5].

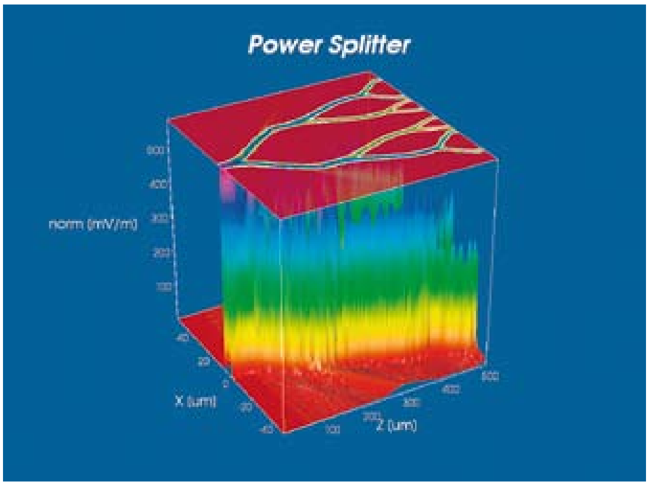

Figure 3. 2D BPM simulation of a 1x4 power splitter.

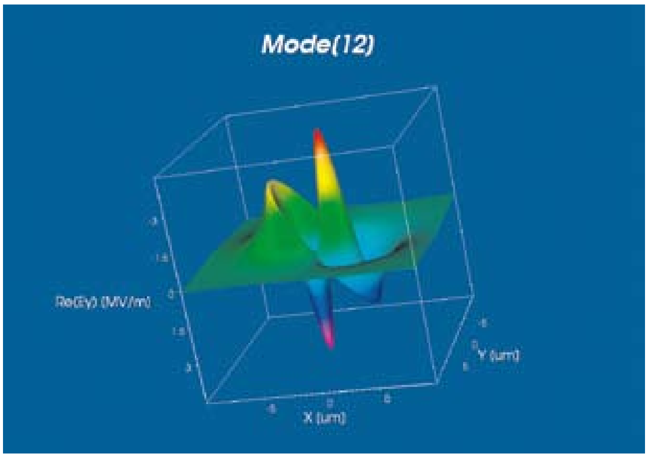

Figure 4. Simulation of an optical fiber mode.

However, unfortunately, the amount of calculation that needs to be performed to design a device has gone up faster than the increase in computer processor speeds can handle. This is in part due to the increased complexity of the devices, in part due to the more advanced simulators, and in part due to the fact that fabrication data is at hand – and thus the effects of fabrication variations on the yield of a device should be calculated. In fact, most actual devices are far too large – with small feature sizes – to simulate even one design at once on a personal computer; one would require supercomputers. So, both the designer and his tools need to become smarter in order to be able to properly design a photonic device. Two examples of how to do this will be discussed briefly: first, by separating the device into building blocks, each of which is manageable, and performing Design of Experiment-like simulations on them, and second, by using an advanced numerical tool.

Building blocks

As an example of the designer using his tools in a smarter way, the widely used Arrayed Waveguide Grating may serve. It was shown in the article by Meint Smit in the June edition of this magazine [6]; see also Figure 5. This methodology to simulate the structures was developed within the European project Apache [7]. These devices are used to separate or combine light of different wavelengths. They come in many shapes and sizes, depending on the technology platform they are created on. Their size can be several centimeters, while the individual waveguides are just a few micrometers wide. These devices are such that the third dimension can be neglected by choosing the parameters of the 2D simulation correctly, and moreover, reflections inside the structure are usually neglected. Even with those approximations, however, the device is too large to simulate in its entirety.

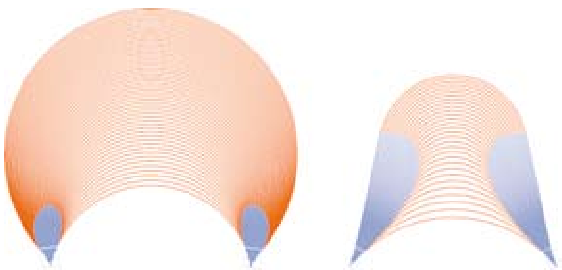

Figure 5. Examples of Arrayed Waveguide Grating layouts.

The first thing that one can do is to identify those parts of the structure that need detailed analysis, and those that can be approximated by simpler models. In this case, the large array of waveguides consists of guides that are completely decoupled – meaning that they do not influence each other. One may thus simulate the input section of the AWG using a 2D BPM method, take the amplitudes of the modes of the array waveguides and simply transfer them with the correct phase to the start of the output section of the AWG, and simulate that section using BPM again. By applying this procedure for each wavelength, the spectrum can be obtained, from which the relevant performance parameters may be obtained. However, this still is a lengthy procedure – each wavelength point may take several minutes.

Another significant speed-up may be gained by using the physical law of reciprocity; the transfer from one port (input mode) of an optical system to another port is the same as from that other port to the first one. This allows one to set up the scattering matrix of the parts of the device with only a few simulation runs, and by proper interpolation between wavelengths the whole spectrum (see Figure 6) can be generated in just a few minutes, and the relevant performance parameters may be obtained in a couple of seconds. Furthermore, the responses of the building blocks vary smoothly with the technological variations (like waveguide width and height and the refractive index of the materials), so one may use Design of Experiment techniques to set up a model for these responses, essentially applying interpolations in the space of technological parameters.

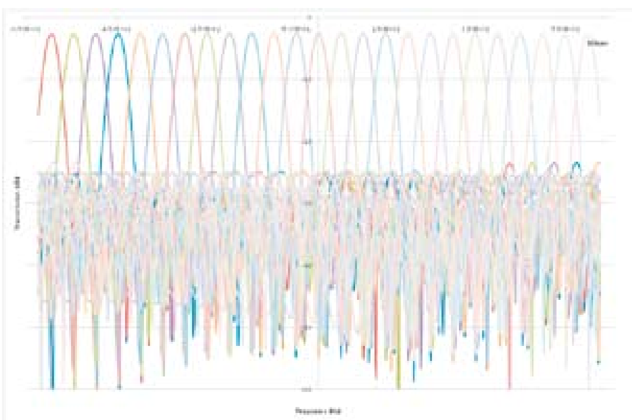

Figure 6. Spectrum of an AWG; the plot shows the response of all 25 output channels.

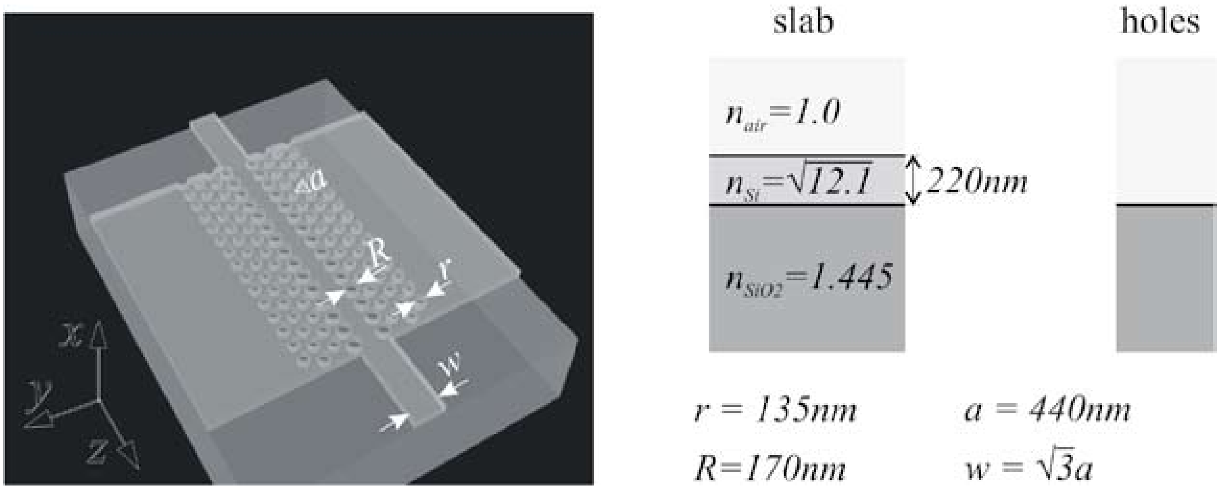

Figure 7. Photonic crystal slab waveguide structure. As denoted in the figure, all critical dimensions are below 1 μm.

Reducing dimensionality of simulations

In other devices, the third dimension is very relevant. As an example of simulation tools becoming more intelligent, we will look at a photonic crystal waveguide. A photonic crystal is a periodic variation of the refractive index in such a way that light propagation is forbidden in a certain wavelength range. One can use two slabs of such a crystal to guide light. The structure in Figure 7 shows an example. It turns out that there is a wavelength region in which this waveguide does not transmit any light, which could be used for sensing applications.

Simulations should be able to predict the location of this so-called bandgap accurately. Fully-vectorial 3D FDTD can be used; it produces accurate results, but it takes a large amount of computer time and memory – on the order of 10 hours and 4 GB on a state-of-the-art personal computer. Traditionally, photonics designers would try to reduce the dimension of the system from 3D to 2D by means of the Effective Index Method – taking a 1D mode of the vertical cross-section at each 2D location. However, for this structure, these 1D modes do not exist in the hole regions, forcing the designer to guess an effective index. He can choose either the index of the substrate or of the air surrounding the structure, but Figure 8 shows that neither predict the location of the bandgap or other features in the spectrum very well. A new method, the Variation Effective Index Method (VEIM) [8], developed at the University of Twente, overcomes this problem, allowing a unique definition of the effective index everywhere, as well as a proper continuous field representation in the whole space. As can be seen in the spectrum graph of Figure 8, the spectral features are much more faithfully reproduced. Figure 9 show a 3D representation of the fields at wavelengths outside and inside the bandgap.

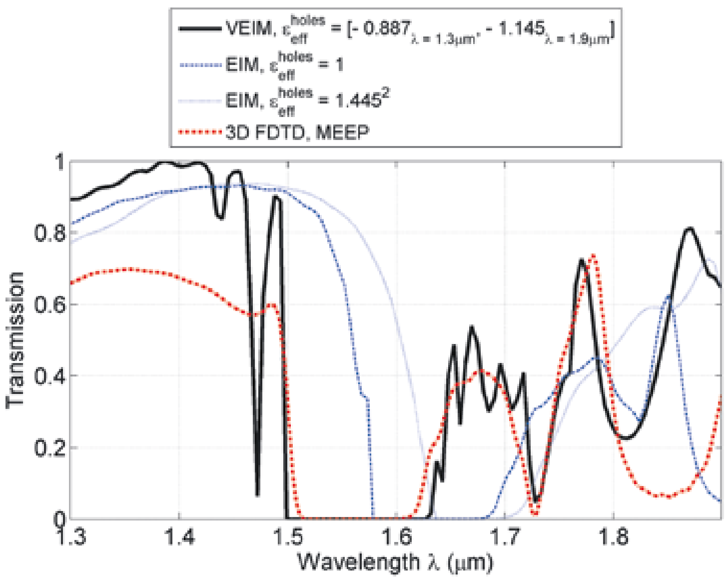

Figure 8. Spectrum of the waveguide of Figure 7. 3D FDTD [5] is more or less accurate, but the calculation is slow; the other calculation methods all have the same (higher) speed, but the VEIM [8] curve is much closer to the FDTD than the more traditional effective index methods.

The way forward

As described in [6], it is expected that foundry-based approaches to PIC design and manufacturing will become a standard in Europe. This approach ties in well with the simulation ideas described here; a foundry can provide its customers with basic building blocks of photonic components, fully characterized including fabrication variations, which designers can combine into an integrated circuit having the properties they desire. Depending on the degree of openness of the foundry, simulations on the building blocks can either be done by the foundry itself (meaning that the foundry does not disclose its real technology and variations, but generates a model of the building blocks including all tolerances) or by the designer, if the foundry discloses the actual processing steps and variations. In either case, smarter simulation algorithms

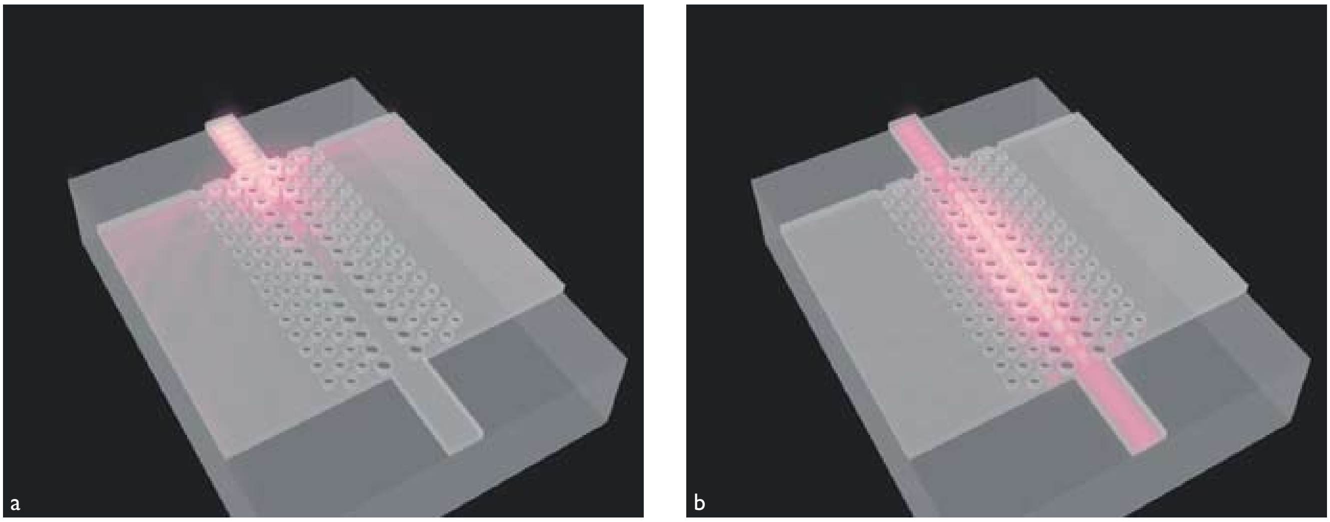

Figure 9. 3D VEIM field of the structure of Figure 7.
(a) At 1568 nm, inside the bandgap.
(b) At 1498 nm, outside the bandgap.

make a designer's life easier and get products into the market faster.

Authors' note

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PhoeniX Software

PhoeniX Software supports more than 120 companies and institutes worldwide to improve quality, reduce time to market, enhance research and automate micro- and nanotechnology fabrication by offering a fully integrated mask layout, process flow design and simulation environment and the only dedicated Manufacturing Execution System and Technology Knowledge Base for the industry, The Living Database. PhoeniX Software is a privately held company, based in Enschede, the Netherlands. Founded in 2003, it has achieved significant presence in the photonics industry as supplier and developer of state-of-the-art photonic simulation tools at the physical and sub-system layer.

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