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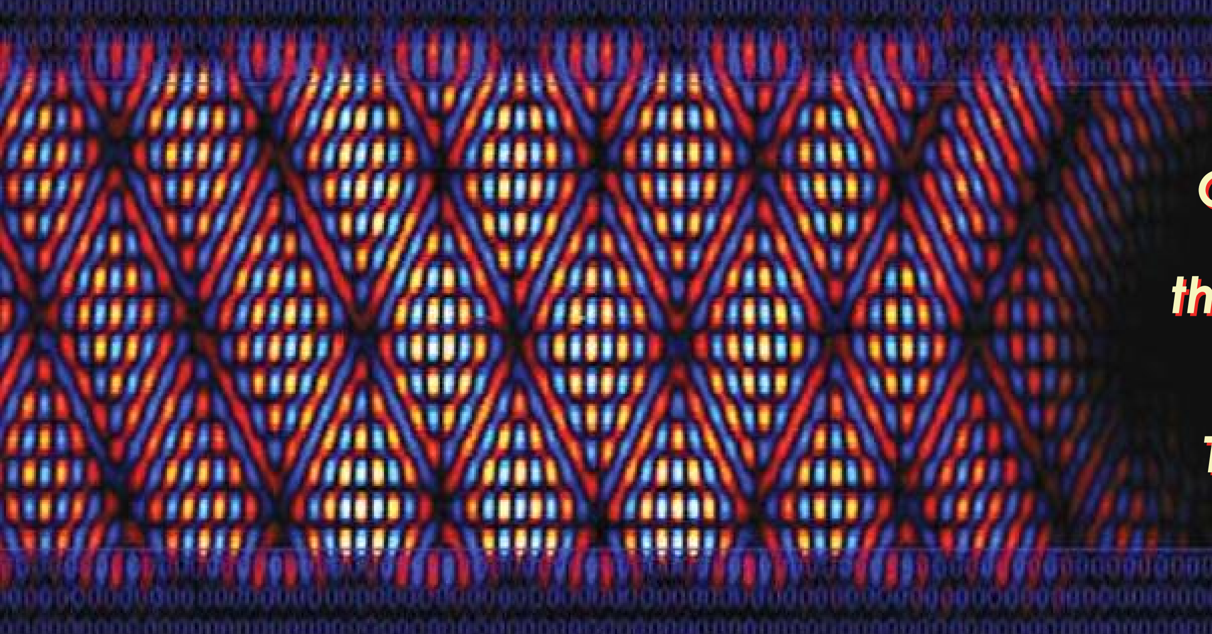
Photonic CAD Matures



Celebrating 25 Years of the IEEE/OSA Journal of Lightwave Technology

IEEE

Industry Research Highlights

Photonic CAD Matures

Dominic Gallagher, Photon Design

Introduction

While electronics has enjoyed quite sophisticated computer based simulation and design tools for decades, only 15 years ago there were virtually no professional commercial tools for the photonics designer and most R&D laboratories were writing their own codes for each specific application. Things have moved a long way since those days and now there is a good choice of tools available to the designer. Nevertheless, in many ways photonic modelling still poses significant challenges due in part to the much larger variety of technologies employed in photonics compared to electronic circuits and there exists no photonic simulation algorithm or even commercial tool that is able to model every sort of photonic circuit. This article aims to give the reader an introduction to the main algorithms of use in photonics modelling, to highlight their strengths and weaknesses and discuss where photonics CAD is going next.

Passive Device Algorithms

This article will focus largely on the techniques for modelling passive photonic devices, where light is propagating in a medium whose refractive index is constant or is at most somewhat dependent on the intensity of the light propagating – (so called non-linear media). Active devices, where light interacts with electrons, play an important part in modern photonics in LEDs, laser diodes and the like but cannot be discussed in depth here for lack of space.

A wide variety of algorithms have been developed for the simulation of passive photonic devices, though only a few have achieved it to mainstream use. We will cover the following mainstream algorithms here in detail:

BPM - Beam Propagation Method
EME – Eigenmode Expansion Methods
FDTD – Finite Difference Time Domain

We will discuss the strengths and weaknesses of each method and give the reader some helpful information on choosing an appropriate tool for a given task.

Scoring an Algorithm

The ideal algorithm would score well in all of the following aspects:

- speed – obvious but crucial for efficient design work
- low memory usage – no point if the simulation doesn't fit in your computer
- numerical aperture – the range of angles that can be accurately propagated. Ideally the algorithm would be completely agnostic to angle.
- Δn – the refractive index contrasts in the device. Ideally the algorithm would deal well with any contrast – Si to air is ~2.5.
- polarisation – it should model all polarisations of light equally well.
- lossy materials – it should be able to model absorbing materials, even metals
- reflections – can it deal with reflections in the device?
- non-linearity – it should be able to model non-linear materials such as Kerr effect.

Table 1: Beam Propagation Method

Aspect	*Performance*	*Score/10*
Speed	FD-BPM scales linearly with area and can take fairly long steps in propagation direction	-
Memory	Usage scales linearly with c/s area	-
NA	Best with low NA simulations. Versions using Pade approximants can model a beam travelling at a large angle but still cannot deal well with light simultaneously travelling at a wide range of angles.	4
Δn	Best with low Δn simulations.	5
Polarisation	Semi-vectorial versions work best. Still problems modelling mixed or rotating polarisation structures accurately	5
Lossy materials	Can model modest losses efficiently. Most versions cannot deal well with metals	7
Reflections	Some success in implementing reflecting/bi-directional BPM but generally avoided due to low speed and stability problems	3
Non-linearity	FD-BPM can model non-linearity.	9
Dispersive	Being a frequency-domain algorithm this is easy	10
Geometries	The BPM grid allows diffuse structures to be modelled easily. Problems modelling non-rectangular structures accurately on the rectangular grid	7
ABCs	PMLs available and work well	9

- dispersive materials – it should be able to model structures where the refractive index is varying with wavelength.
- arbitrary geometries – some algorithms can model circular structures well, others rectangular. The ideal algorithm would model all geometries equally well.
- ABCs – a good algorithm should be capable of implementing an absorbing boundary condition such as the PML to absorb light hitting the boundaries of the computation domain.

We will judge our contenders against these criteria.

The Beam Propagation Method (BPM)

This is perhaps the first widely used algorithm and remains today a workhorse for the industry. There are two main variants of the algorithm, the so called FT-BPM (Fourier Transform-BPM) and the FD-BPM (Finite Difference-BPM). BPM is an axial algorithm in that it assumes that the light is travelling more or less in one direction. Newer so called wide-angle BPM algorithms significantly improve accuracy for off-axis propagation. First BPM algorithms were scalar in that they ignored the polarisation of light. These were followed by algorithms that could model TE-like and TM-like polarisations successfully and the newest algorithms have some success at modelling light of arbitrary and changing polarisation.

The key idea of BPM is to remove the fast varying term $\exp(j\hat{\beta}z)$ from the fields (where $\hat{\beta}$ is some characteristic propagation constant) and then to solve the now slower

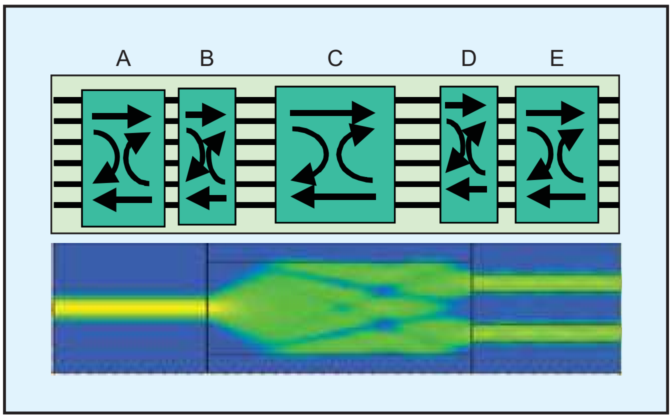


Figure 1 Modelling an MMI using EME. Within each section the fields are represented as a sum of local modes. Coupling between modes occurs only at the interfaces. The MMI can be decomposed into 5 simpler s-matrices as shown, so that even if one changes you can re-use the others, saving much time when doing a set of similar simulations.

Table 2. Eigenmode Expansion Methods

Aspect	*Performance*	*Score/10*
Speed	EME scales poorly with cross-section area – as A^3 (A is c/s area). However it can efficiently model very long structures especially if their cross-section changes only slowly or occasionally. Periodic structures scale as log(number of periods) – so can compute efficiently. S-matrix approach allows a set of similar simulations to be done very quickly – parts of previous calculation can be reused.	-
Memory	Memory increases at rate between A^2 and A^3 (A is c/s area), but very efficient for long or periodic devices.	-
NA	Can model wide-angle beams by increasing the number of modes in the basis set at expense of speed and memory.	7
Delta-n	Rigorous Maxwell Solver can accurately model high delta-n	8
Polarisation	Rigorous Maxwell Solver is polarisation agnostic	10
Lossy materials	Depends on mode solver used.	7
Reflections	Yes – easy and stable even when there are many reflecting interfaces.	10
Non-linearity	Difficult – have to iterate, and then only modest non-linearity levels will converge	3
Dispersive	Being a frequency-domain algorithm this is easy	10
Geometries	Depends on the mode solver used. Can use different structure discretisations in different cross-sections, so solver can better adapt to the geometry.	7
ABCs	Depends on the mode solver used. E.g. a finite-difference solver can be readily constructed to implement PMLs. However, PML's are more difficult to use with EME than with BPM or FDTD.	7

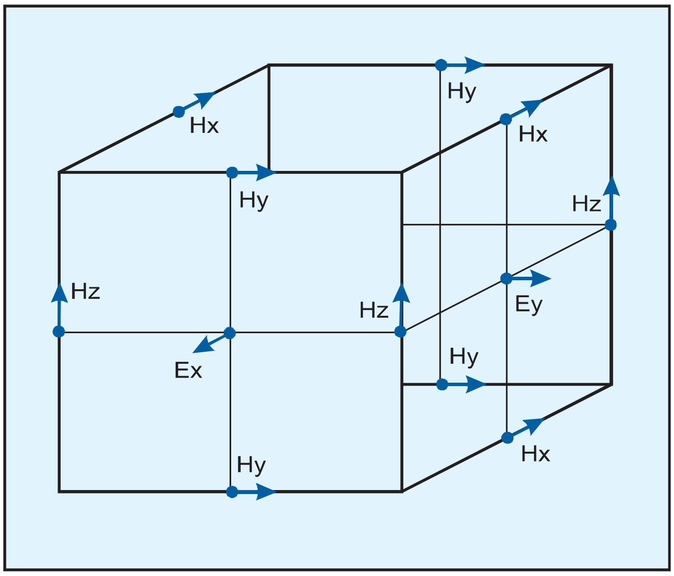


Figure 2: The Yee cell of FDTD, showing the position of the 6 EM fields on the cell surface. This staggered grid makes the algorithm more accurate.

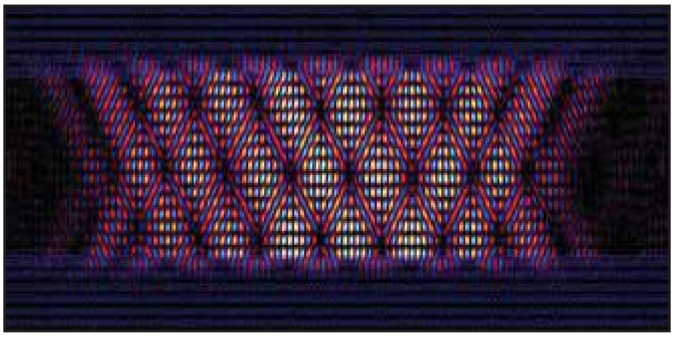


Figure 3 A photonic crystals laser oscillating in a "Littrow" mode; simulated using CrystalWave's active FDTD algorithm which couples the light to the electron population of the laser's active region.

varying fields. It works well for modelling waveguide components such as tapers and y-junctions especially with modest Δn (refractive-index contrast). It struggles to give accurate results for silicon nanowire technologies, where both Δn is high and, because of tight confinement the light is effectively travelling at a large range of angles from the device axis.

Table 1 summarises different aspects of BPM performance, with scores out of 10 for each aspect. Speed and memory performance are not given scores since these depend too much on the application – BPM might be fastest for one application and FDTD for another.

Eigenmode Expansion Methods (EME)

This term covers a variety of algorithms that decompose the electromagnetic fields in terms of a sum of local eigenmodes. Bidirectional eigenmode propagation (BEP) has been widely developed by our company into a viable alternative to the BPM algorithm and provides several advantages for certain applications. We will discuss here the BEP variant.

The principle of EME can be encapsulated in the following equation for the propagation of light in a waveguide (i.e. that is not varying in the z-direction):

$$\underline{E}(x,y,z) = \sum_m \underline{\mathsf{E}}_m(x,y)\cdot(c_m^+ .e^{i\beta_m z} + c_m^- .e^{-i\beta_m z})$$

electric field

$$\underline{H}(x,y,z) = \sum_m \underline{\mathsf{H}}_m(x,y)\cdot(c_m^+ .e^{i\beta_m z} + c_m^- .e^{-i\beta_m z})$$

magnetic field

where $\underline{\mathsf{E}}_m(x,y)$ is the electric field profile of the mth mode, β_m is its propagation constant, and c_m^+, c_m^-, are the amplitudes of the mode in the +z and −z directions respectively. Having an expansion in terms of a complete set of modes permits one to write a scattering matrix for any component in the form:

$$\begin{pmatrix} \underline{v}_{lhs} \\ \underline{v}_{rhs} \end{pmatrix} = \underline{\underline{S}} \begin{pmatrix} \underline{u}_{lhs} \\ \underline{u}_{rhs} \end{pmatrix}$$

where $\underline{u}_{lhs}$ and $\underline{v}_{lhs}$ are the vector of amplitudes of the modes entering and exiting (respectively) the left hand side. These few equations immediately illustrate some useful features of EME:

- it is fully bi-directional; in fact it can be made almost omni-directional if sufficient modes are used.
- it is a fully vectorial algorithm, making no approximations of the polarisation of the light.
- it is a rigorous solution to Maxwell's Equations; the main approximation being the finite number of modes used.
- The scattering matrix approach means that you solve the problem for all inputs simultaneously, so you can for example get the response for both TE and TM polarisations in one go. It also allows you to divide a large circuit into multiple parts and then re-use the s-matrix of the parts again potentially saving a lot of time.
- It allows efficient modelling of periodic or repeating structures since one can evaluate the s-matrix of one period and then re-use it.

Table 2 summerizes various aspects of EME methods.

The Finite-Difference Time Domain (FDTD) Algorithm

This is perhaps now the most widely used algorithm for the solution of Maxwell's Equations. It is a brute force finite-difference discretisation of Maxwell's Equations in time and space. In principle it can model virtually anything, given enough computing power. It is also very simple to implement – the basic algorithm can be written in 30 lines of code.

The dominant FDTD algorithm dates back to Kane Yee in 1966 but variants with e.g. triangular grids have appeared more recently. Table 3 summerizes FDTD aspects.

Comparing BPM, EME, FDTD

The score tables given above do not of course tell the whole story. The following "applicability diagrams" show graphically how the three algorithms fair in response to varying numerical aperture, cross-section and length.

Figure 4 shows how the FDTD, BPM and EME algorithms fare with varying Δn and device length. FDTD due to its small grid size cannot do very long things. However it can deal with high Δn structures. BPM can do much longer things but cannot deal well with high Δn structures. EME can model the longest structures such as a fibre taper efficiently and can also deal with high Δn devices accurately.

Figure 5 shows how the FDTD, BPM and EME algorithms fare with varying numerical aperture (range of angles) and cross-section size. FD-BPM can cope with the largest cross-section sizes due to its order-N algorithm, but cannot cope well with light travelling at a wide range of angles. FDTD can do omnidirectional simulations (large NA), but smaller cross-sec-

Table 3. Finite Difference Time Domain

Aspect	*Performance*	*Score/10*
Speed	Scales as V (device volume) but grid size is small so not as good as BPM or EME for long devices.	-
Memory	Scales as V (device volume) but grid size is small so not as good as BPM or EME for long devices.	-
NA	Omni-directional algorithm is agnostic to direction of light – great when light is travelling in all directions	10
Delta-n	Rigorous Maxwell solver, happy with high delta-n, but slows down somewhat with high index.	9
Polarisation	Rigorous Maxwell Solver is polarisation agnostic	10
Lossy materials	Can model even metals accurately with a fine enough grid and small modifications to the algorithm.	
Reflections	Yes – easy and stable even when there are many reflecting interfaces.	10
Non-linearity	Yes – non-linear algorithm relatively easy to do	9
Dispersive	Have to approximate the dispersion spectrum with one or more Lorentizans but exact fit to the spectrum over a wide wavelength is difficult and the algorithm also slows down.	7
Geometries	Fine rectangular grid can do arbitrary geometries easily, though there are problems approximating diagonal metal surfaces	8
ABCs	Yes – very effective and easy to use	9

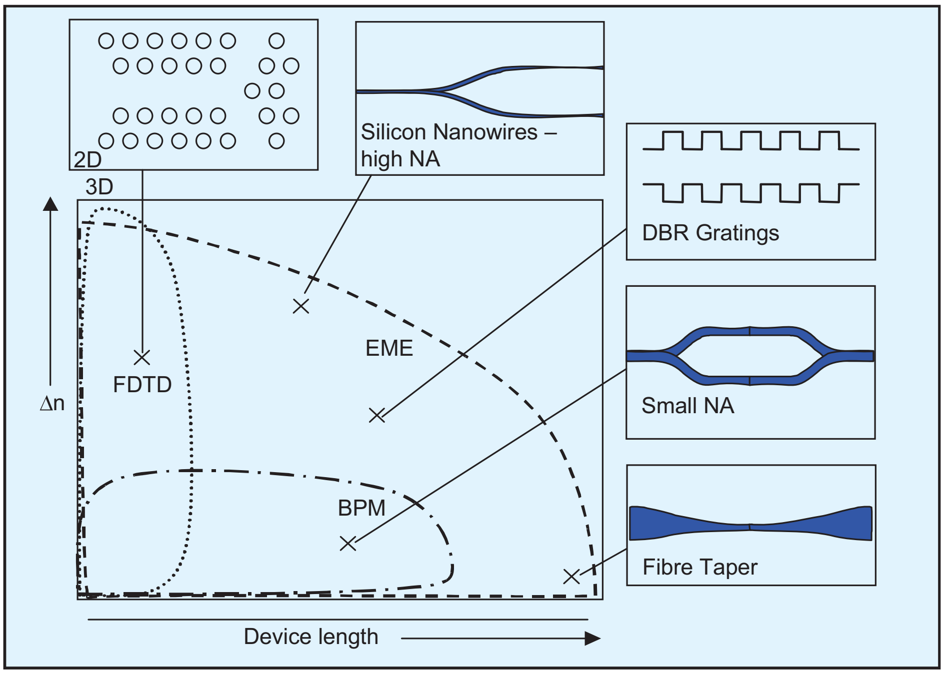


Figure 4 Showing the domains of applicability of FDTD, BPM and EME to varying Δn and device length.

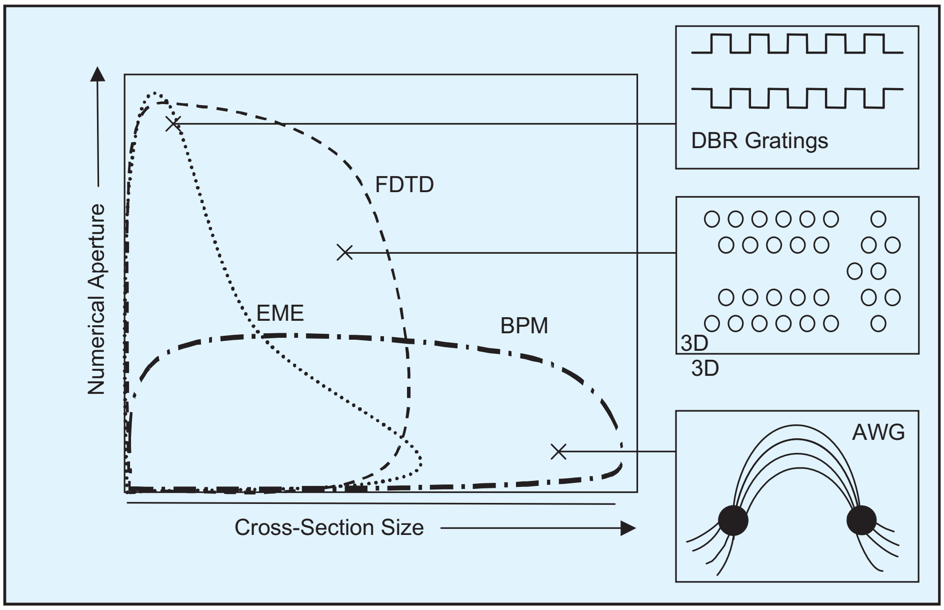


Figure 5 Showing the domains of applicability of FDTD, BPM and EME to varying numerical apperture and cross-section size.

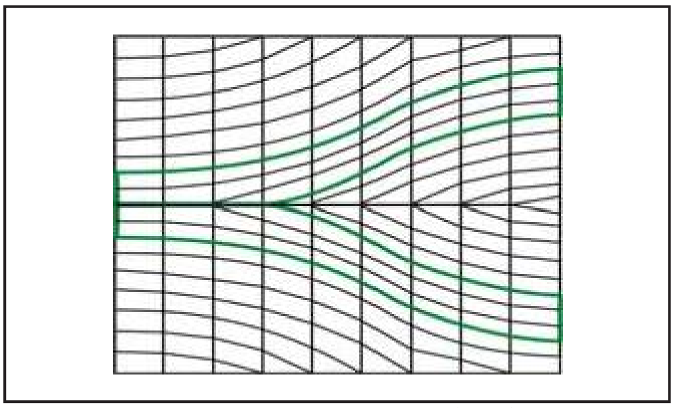


Figure 6 Improved meshes for BPM. A mesh (black) able to conform to the structure (green) substantially improves accuracy.

tions than BPM due to its fine grid. EME can do high NA or large cross-section but not both, since high NA and large sections both require one to increase the number of modes used and this number would become impractical.

Evolving BPM

Despite its age, significant advances are still being made in the BPM algorithm. For example in recent times, the efficient ADI technique has been combined with Pade approximation methods to significantly speed up the speed of computation at some expense of accuracy and even this accuracy cost has now been reduced substantially. Hadley, responsible for the original Pade modifications of BPM, has demonstrated work on slanted meshes that are able to conform to the boundaries of the structure – see Figure 6. Many other workers are still actively engaged in developing BPM further.

Evolving FDTD

One of FDTD's big limitations is it's regular rectangular grid. This means that one is limited to using the same resolution everywhere, unlike a finite element algorithm which can reduce the resolution locally and also allow the grid to follow the contours of a structure. One solution to this is sub-gridding which we have implemented in our own FDTD tools – see Figure 7. The sub-gridding can be cascaded so that you could have 1/4, 1/8 or smaller local grids. For a 3D simulation, using a 1/4 subgrid over a small part of your structure can increase the speed of the simulation by up to 64 times over a uniform grid. The challenge however in sub-gridding is to prevent artificial reflections occurring at the boundaries of the sub grid and main grid. However we have recently demonstrated algorithms that exhibit reflections below 10^{-8} effectively eliminating this problem – see Figure 7.

Another promising alternative to the FDTD algorithm is the so-called pseudo-spectral time domain method (PSTD). The structure is broken down into sub-domains of uniform index so that the domains follow the boundaries of the device as shown in Figure 8. Within each domain the fields are represented by expanding in an appropriate basis set ϕ_n, typically Chebyschev polynomials

$$u(x) = \sum_{n=0}^{N} c_n \phi_n$$

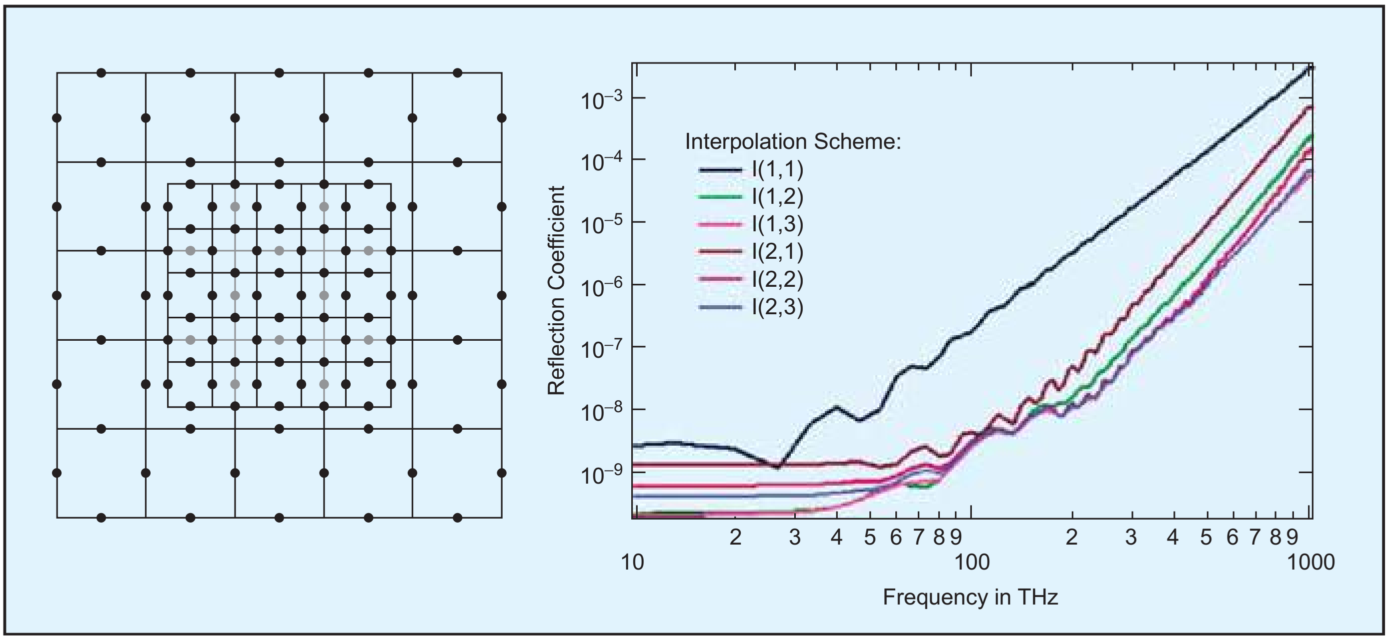


Figure 7 (left) scheme for sub-gridding FDTD, allowing additional resolution where needed; (right) different interpolating schemes for stitching sub-grids to main grid.

The method allows a varying grid size and conformation to curved surfaces and is ideal for circular or spherical metal objects where FDTD struggles.

Photonic ICs – the next stage

EME and associated scattering-matrix algorithms are ideal for the next level in photonics CAD – modelling not just individual components but whole circuits of components. Once a scattering matrix for a linear component has been evaluated then any signal can be propagated through the device. However active components can not be easily modelled using frequency domain algorithms and a circuit including active elements must be simulated in the time domain. A powerful technique for doing this is the so called time domain travelling wave (TDTW) algorithm, which we have pioneered over a number of years and have now developed into a flexible photonic circuit simulator .

The basis of the algorithm is beautifully simple. We assume that light is travelling forward or backward along a waveguide. We then remove the fast changing part $e^{i(\beta z-\omega t)}$ to leave forward A(z) and backward B(z) fields that vary slowly in both time and space. We can then write the advection equations for these fields as follows:

$$\frac{1}{v_g}\frac{\partial A}{\partial t}+\frac{\partial A}{\partial z}=j.\kappa.B+(g-j.\delta)A+F_A(N_e)$$

$$\frac{1}{v_g}\frac{\partial B}{\partial t}-\frac{\partial B}{\partial z}=j.\kappa.A+(g-j.\delta)B+F_B(N_e)$$

grating feedback, gain, detuning

This can be solved in the time domain rather like FDTD but now with much larger time and space steps because we have removed the fast varying parts. The cost is of course that it can only model fields propagating in +z or −z directions. However just like FDTD it can propagate many wavelengths at a time. Noise sources such as from spontaneous emission can be readily supported and propagated through the circuit by setting the forcing terms F in the previous equation.

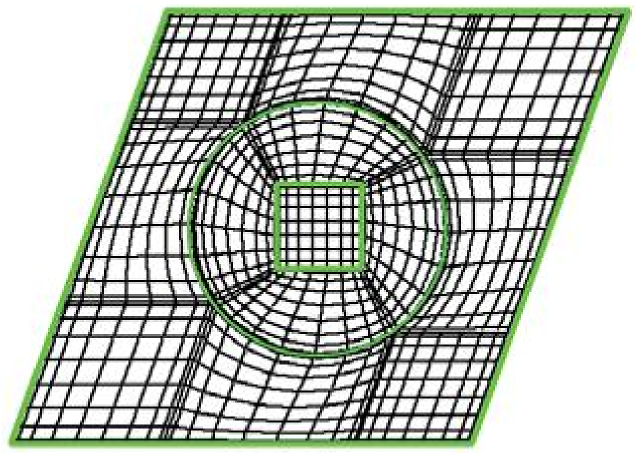


Figure 8 Discretisation of a square in a circular in a rhombus for the Chebyshev method. The grid follows the structure, giving better performance.

We illustrate the flexibility of the approach by the simulation of an all-optical 2R regenerator . The circuit is shown schematically in Figure 9. It consists of a Mach-Zehnder interferometer with an SOA in each arm. Blue rectangles are waveguides and green rectangles are power splitters/combiners. Figure 10 shows the input to the regenerator – with a slow rise time, on/off ratio of just 5 and amplitude of 1mW. On the right is the regenerated signal, with >20mW signal, on/off ratio of >30:1 and improved timing. The increased noise is

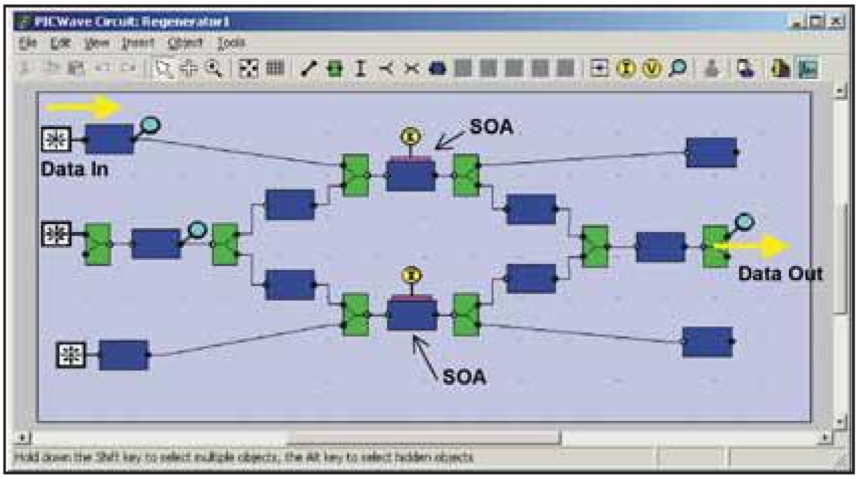


Figure 10: a 2R optical regenerator, consisting of a Mach-Zehnder interferometer with an SOA in each arm.

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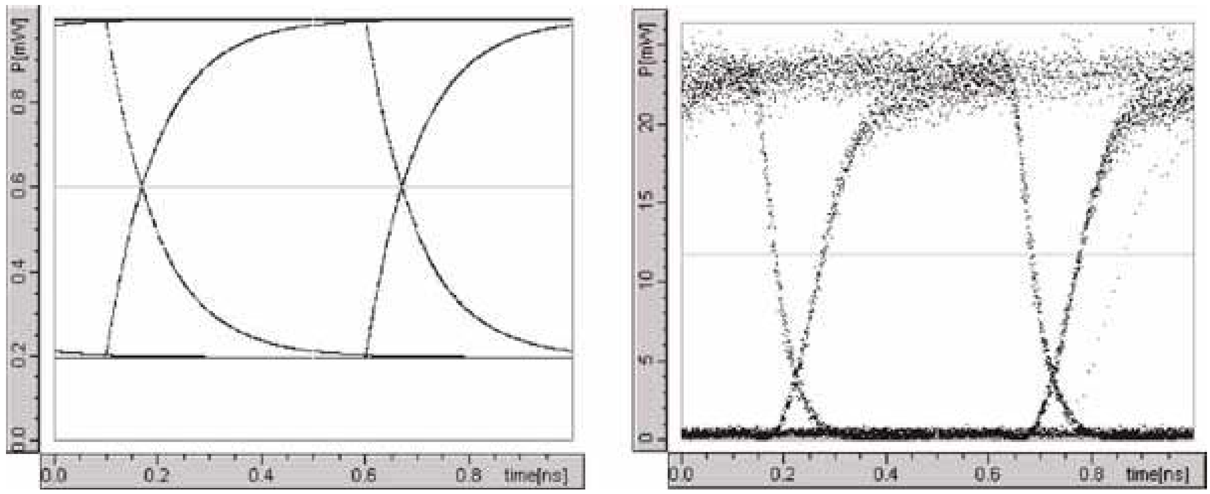

Figure 11 showing input (left) and output (right) from the 2R regenerator.

due to the spontaneous emission in the SOAs illustrating the power of the algorithm to realistically model real devices.

Where to next?

The perfect algorithm has yet to be written. In fact it never will – there will always be one algorithm better for one application and another for a different one. Thus we are likely to see increasing development of multi-algorithm simulation tools that use different algorithms for different parts of a simulation, perhaps even automatically.

Will photonics ever see the existence of tools equivalent to those in electronics that can accurately and readily model millions of transistors? Probably not – photonics uses a much more diverse range of technologies than electronics and the market is much smaller, but certainly we are likely to see some great improvements in the usability, speed and accuracy of photonics CAD in the next few years, as the photonics IC becomes established.

[9] http://www.photond.com/products/picwave.htm
[10] G. Maxwell et al, "Very low coupling loss, hybrid-integrated all-optical regenerator with passive assembly", paper PD3.5, ECOC 2002, Copenhagen (2002).

Biography:

Dominic Gallagher was born in Wales in 1962 and received a BA degree in physics from the University of Cambridge in 1984. In 1987 he obtained a PhD also from the University of Cambridge, for a thesis in optoelectronics. The next two years he was a Research Fellow at Cambridge, working on optical logic designs. In 1989 he moved to Germany to work for the Fraunhofer IAF in Freiburg, providing design support for a project to develop high speed laser diodes and another on inter sub-band photodetectors employing novel grating techniques. In 1992 he returned to the UK to start up Photon Design which he has grown into a major international player in the photonics CAD tools market in the intervening years.