A Modern Photonic CAD Environment

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Photonics has been for many years the mainstay of the telecommunications industry – almost all data travels most of the time in an optical fibre. This started with the long-haul links in the 1980s then including the metro-area links in the 1990s. Now even a 20m connection between two computers in a data centre is likely to be via an optical fibre. But the really exciting work is now being done by the big silicon electronics vendors – the likes of Intel, IBM. These companies are working hard to try to integrate photonics with tomorrow's CPUs.

Our company Photon Design is at the forefront of the move to photonic integration. This article will highlight some of the innovations that we have been driving and also hopefully provide a useful introduction to the technology of photonic integration.

1 Passive Waveguide Components

1.1 Dielectric Waveguides

Modelling of almost all photonic devices should start with the design of passive waveguides. We want to find the eigenmodes of the waveguides, i.e. solutions of Maxwell's equations of the form:

$$E = e(x,y).\exp(i.\beta.z) \qquad H = h(x,y).\exp(i.\beta.z)$$

There are many methods to solve this problem. The most popular are finite difference (FD) and finite element (FE) methods. Figure 1 below shows a FD and a FE mesh of a silicon waveguide, generated using the advanced meshing capabilities of FIMMWAVE – note how the mesh elements get smaller in the silicon and even smaller at the boundaries. To the right you can see the resulting mode profile (E-field) computed by FIMMWAVE.

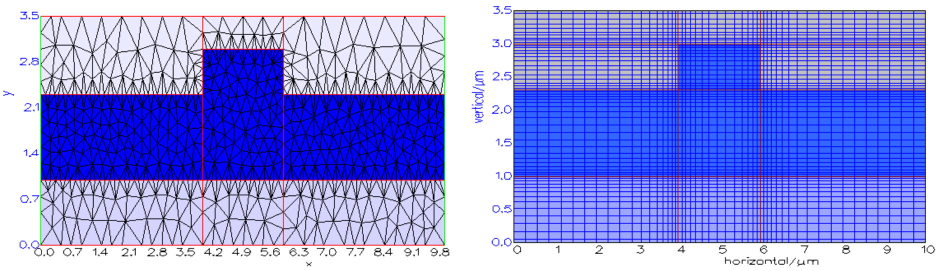


Figure 1 (left) a finite-element mesh; (mid) a finite difference mesh.

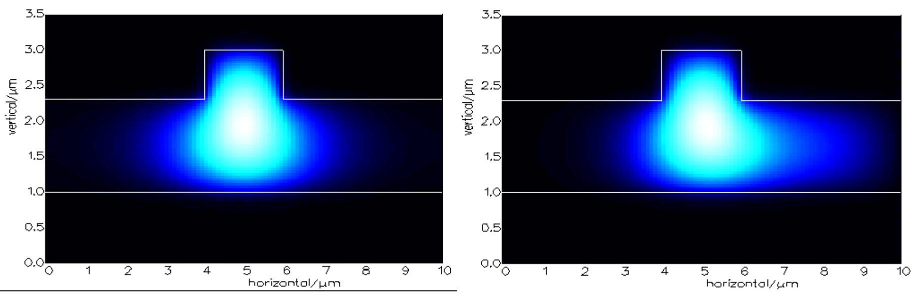


Figure 2 (left) ; the fundamental mode of a silicon-on-silica waveguide computed by FIMMWAVE. (right) the mode of the same waveguide but with a 1mm bend radius.

When a waveguide is bent, the optical mode will in general start to leak out. This has to be carefully managed by the photonics designer so tools like FIMMWAVE are vital to a successful desing. Here we predict a loss of ~1/cm – too high for most applications. This design of waveguide is not suitable for navigating bends and will need altering.

1.2 Tapered Waveguides

With the popularity of silicon photonics, photonics waveguides have shrunk to very small sizes – a typical silicon-on-silica waveguide is just 220nm thick. But they still need to be coupled to an optical fibre – whose mode diameter is typically 9um. Many solutions to this problem are used. One is to use a tapered waveguide as shown in Figure 3 (left). As the silicon waveguide gets smaller, the mode expands to fill the whole polymer box. This poses some challenges to a simulator – the device is big – maybe 300um long, but has very small features. Photon Design has pioneered a technique called Eigenmode Expansion (EME), releasing the first useable 3D EME tool in 1998 that solved what is called the EME “staircasing problem” – in a tool called FIMMPROP[1].

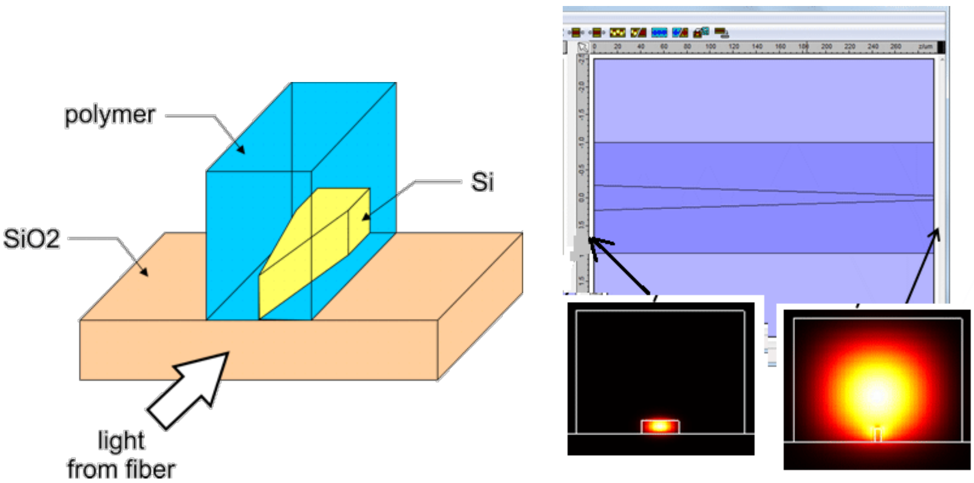
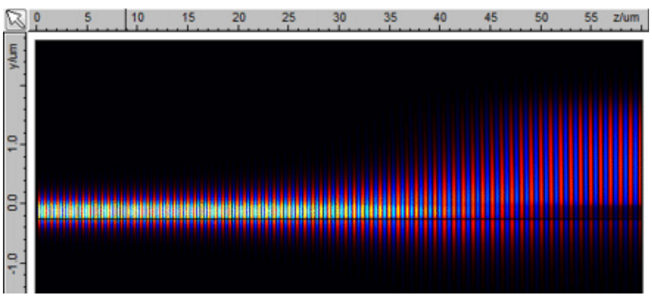


Figure 3 (left) schematic of a waveguide taper. (right) simulation of the inverse taper.



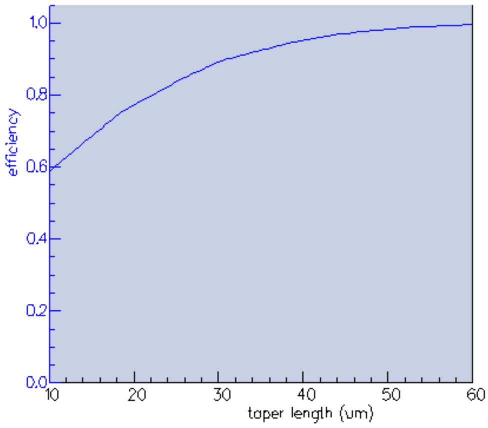


Fig 4 (left) the electric field seen from the side showing how it expands as the silicon core shrinks. Thanks to advanced techniques this takes just 20s on a Core i7 – a small fraction of the time needed by competing techniques like FDTD. (right) a scan of efficiency simulating 100 more devices in just 2.5s.

EME is ideal for this application because a) it is a rigorous solution of Maxwell's Equations, and b) it can take large steps in the propagation. No other method can offer both these benefits. A n extensive discussion of this can be found here[2]. One other large benefit that EME offers, fully exploited in FIMMPROP is the ability to alter parts quickly. The above taper takes about 20s to reach modest accuracy. Some similar structures might take an hour or two to simulate. One thing the designer needs to know is "how long should it be to get e.g. 95% efficiency?". Because of the technology in FIMMPROP, even if the first simulation takes 20s, we can simulate another 99 simlar devices with different taper length in just 3 seconds! The graph in Figure 4 (100 points) was generated in 2.5s on a Core i7 PC.

1.3 Ring Resonators

Wavelength division multiplexing (WDM) – where one sends multiple channels down an optical fibre at different wavelengths is a widely used technique for increasing data carrying capacity. One technique for removing one channel from a waveguide carrying multiple wavelengths is the ring resonator – illustrated in Fig 5 below. Small ring resonators are often simulated in FDTD. Photon Design has developed a Finite Element Time Domain (FETD) that has many advantages over FDTD. One is illustrated in Figure 5. There is usually very little light in the middle of the ring. With FETD it is easy to make a "void" in the mesh and save simulation time. The right hand figure shows the resulting simulation. A pulse of light containing a broad spectrum of wavelengths has been injected from the bottom left corner. Only one wavelength has coupled to the ring and it is steadily coupling it to the exit at top left.

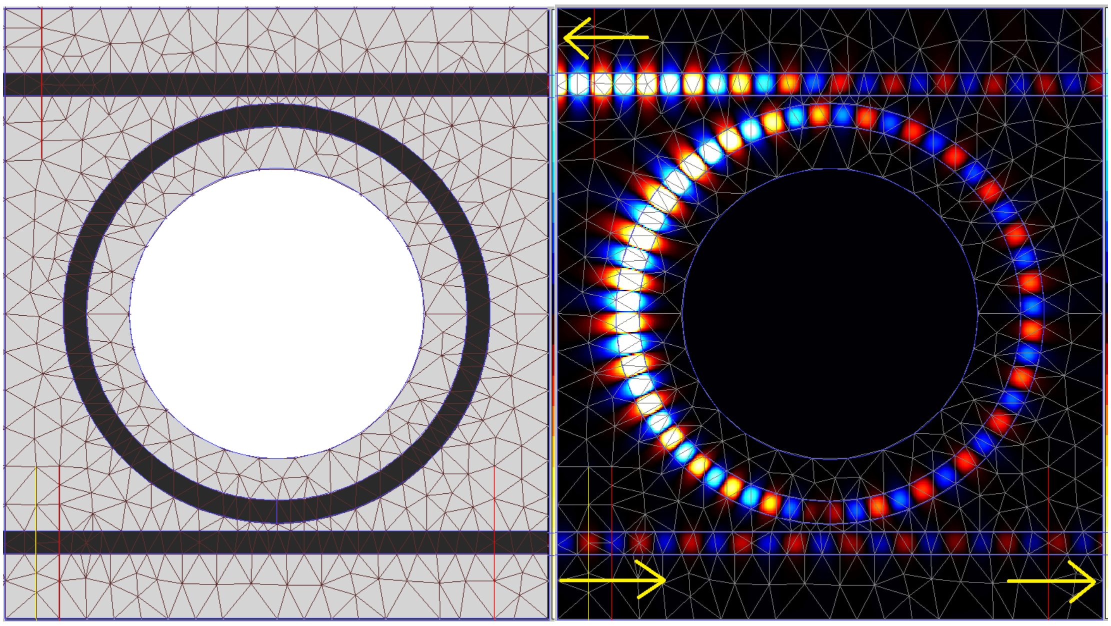


Fig. 5. (left) a ring resonator. The dark regions are the waveguides. The triangles are from the mesh used by OmniSim/FETD – a finite element method. Note the void - where no light is found – this speeds up the simulation.

As the ring gets larger, the use of mesh voids becomes more beneficial but eventually there comes a point that even this technique is very slow. In this case it is better to return to EME. In EME we will break the ring resonator down into parts as illustrated in Fig 6.

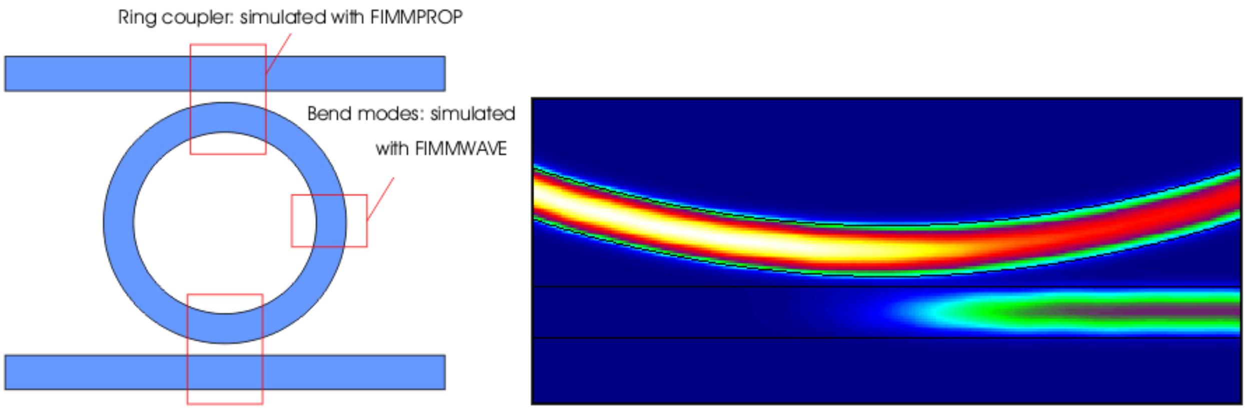


Figure 6 (left): breaking the ring resonator into parts. (right) simulation of the ring coupler in EME (FIMMPROP). Light is launched into the "bend mode" of the ring at top right.

2 Active Photonic Integrated Circuits .

Photonics is moving to ever higher levels of integration. This means that many photonic chips need to include gain functions as well as passive waveguides. We will discuss the techniques needed to model active photonic integrated circuits (PICs).

2.1 A Simple Laser Diode

The most popular source of light on a PIC is the quantum well diode laser. The "quantum wells" trap the injected electrons into a confined space, improving efficiency. Figure 7 shows the band structure of a typical InP QW laser, computed with our Harold simulator, together with the resulting light-current curves. These calculations bring together many different branches of physics – quantum mechanics, electron drift and diffusion, thermal diffusion, and of course the electromagnetic propagation of the emitted light. Managing the complexity of all these effects is a challenge for a simulator – it is unrealistic to take everything into account and approximations have to be made, without compromising the result. This has been the key goal and challenge of Photon Design's laser models PicWave and Harold.

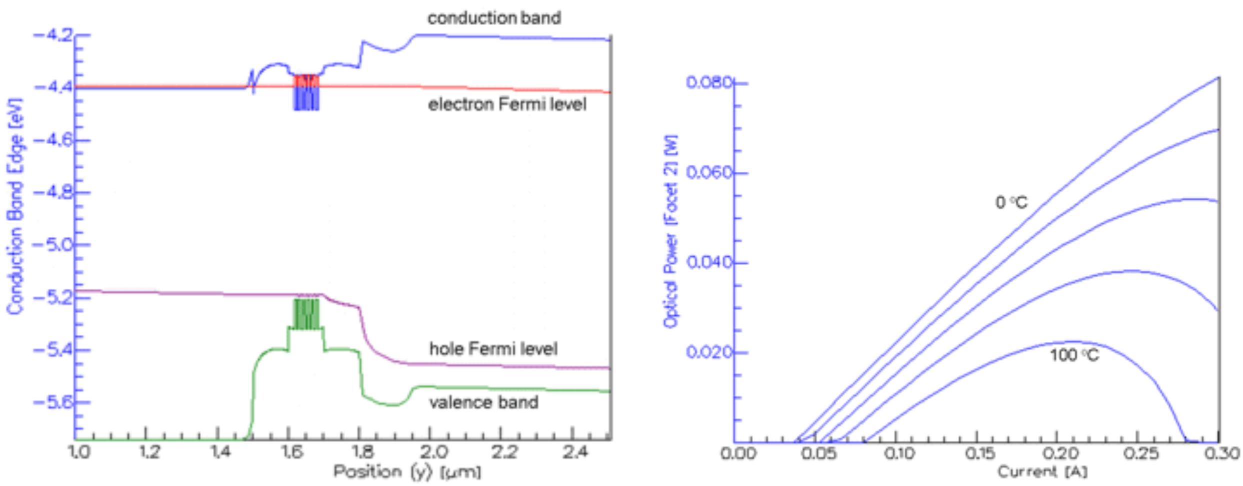


Fig. 7 (left) the band structure of a quantum well InP laser. The 6 wells can be seen at positions 1.6μm to 1.7μm. (left) the corresponding light-current curves of the laser diode at different temperatures. Note how the efficiency drops off rapidly as the temperature increases.

2.2 A Tuneable Laser

WDM systems require careful control of wavelength. A modern WDM system can have 80 wavelengths. If these are supplied by fixed wavelength lasers then one requires 80 different lasers for each transmitter – a severe logistics cost. The solution is to make a laser that can tune over all 80 channels. A popular design is the sampled-grating DBR laser – fig. 8. This operates on a Vernier effect. Gratings A and B are designed to have a comb shaped reflection spectrum with slightly different spacing. By adjusting the currents in the two gratings and the "Phase Section" one can vary the lasing wavelength typically over 20-30nm. The device can be readily simulated in our PicWave tool. PicWave is a time-domain based laser diode and active PIC simulator that is widely used by leading laser diode manufacturers around the World. Figure 9 (left) shows some time-resolved spectrum of the SG-DBR laser as the current to just one grating is varied. The second figure shows a correctly controlled SG-DBR laser tuning continuously over 5nm.

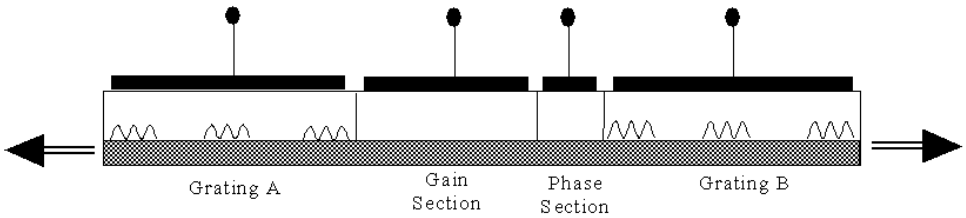


Fig. 8 (top) schematic of a SG-DBR tuneable laser.

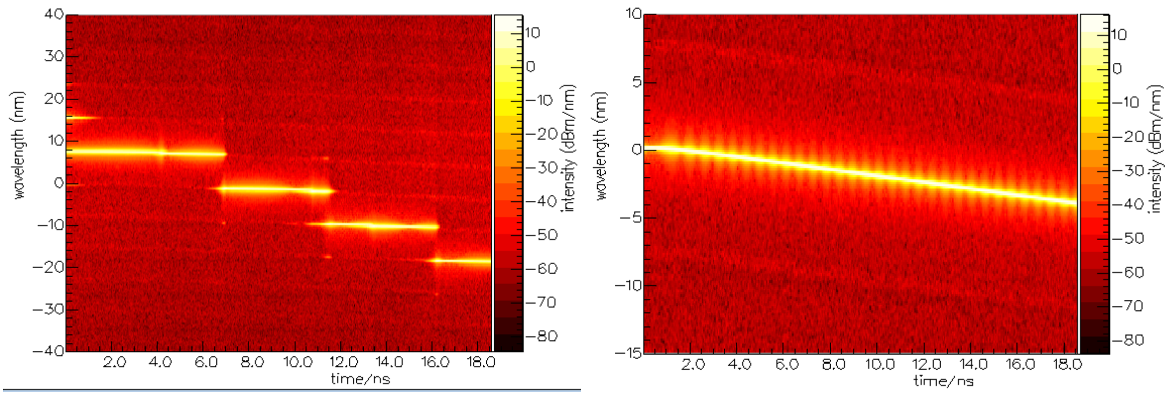


Fig 9 (left) time-resolved spectrum of SG-DBR laser, varying current to just one grating showing mode hops. (right) a correctly controlled SG-DBR laser.

2.3 A Hybrid Silicon/InP Laser Diode

Photonics is coming to your computer CPU – it is the only way to improve the data flow rate around a computer. Already most power in a CPU is taken up in sending data around the CPU and to/from memory – not in the logic transistors. Sending data via light has the potential to improve matters. To do so, the CPU will need a light source. This could be generated off chip and then injected into the CPU just like the electrical power supply. Better would be to integrate the laser directly on the CPU. Unfortunately silicon makes for a lousy laser due to its indirect band gap. So many groups have been working on trying to bond InP on top of silicon – the so-called "hybrid" chip. A cross-section of such a laser is shown in Fig 10 (left). One challenge with this idea is how to get the light down from the InP laser into the passive waveguides in the silicon. Fig. 10 (right) shows one idea – to taper the laser waveguide down until the light has nowhere else to go but into the silicon. The path of the light can be seen in the figure – simulated with FIMMPROP.

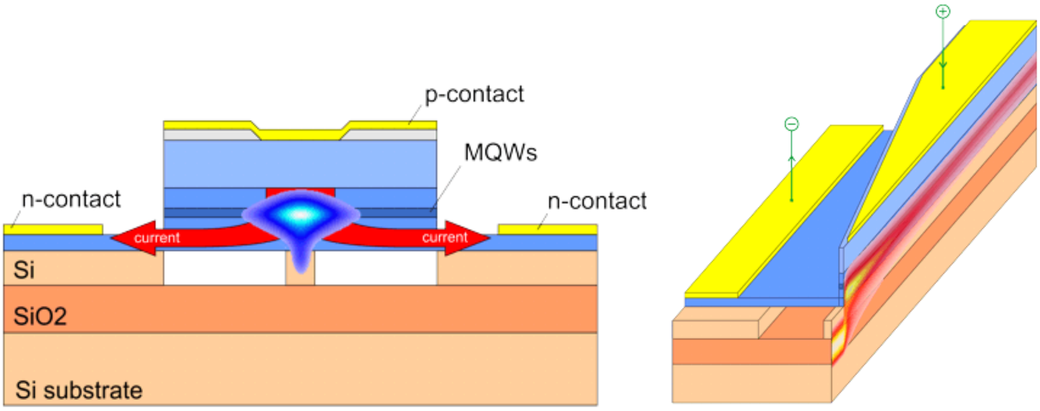


Fig 10 (left) cross-section of a hybrid silicon/InP laser diode. (right) the tapering required to get the light down into the silicon.

To optimise this device we need to simulate the whole structure – including the complex electrical flows, the charge carrier diffusion and recombination, and of course the light flows in the tapered InP laser and the silicon waveguides where the laser mirrors are typically found. PicWave can model all these effects – see fig 11.

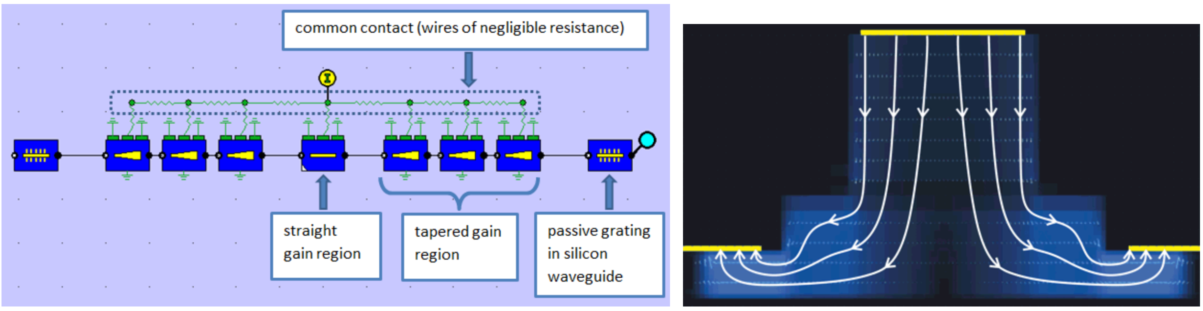


Fig 11 (left) schematic of PicWave's Si/InP hybrid laser simulation. (right) the current flows in the InP.

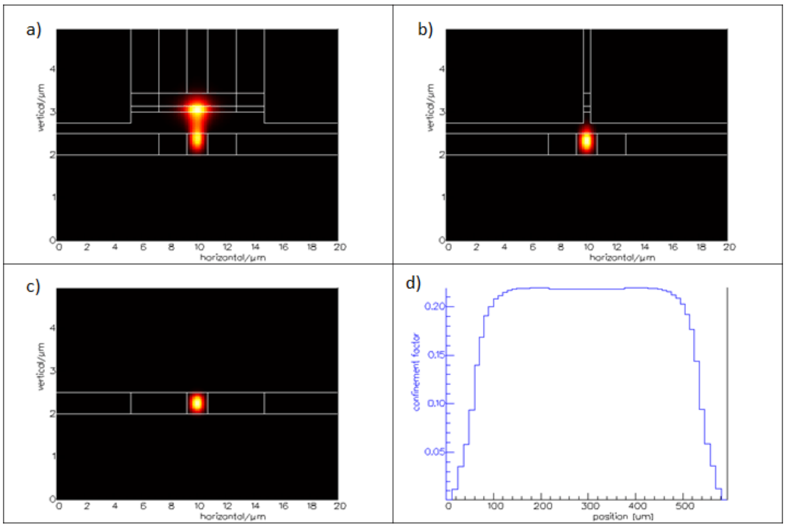


Fig 12 Optical mode in (a) straight gain section – distributed between InP ridge and silicon waveguide beneath, (b) end of taper – now largely confined to silicon waveguide, (c) silicon waveguide grating section; (d) shows the longitudinal profile of quantum well confinement factor along entire length of electrically pumped region.

2.4 Design Kits

Designing photonics from scratch requires a great deal of expensive expertise. This limits the applications of photonics to companies who can afford the huge cost of acquiring such expertise. The photonics industry is addressing this situation by moving towards a "design kit" environment whereby a company with little photonics experience can purchase a ready-made and tested library of photonic building blocks – the Design Kit – then the company's designer need only connect up the building blocks to suit their application. This approach is faster, less error-prone and significantly cheaper. There are now on the market many foundries supporting this approach, both silicon foundries for passive PICs and InP foundries for active PICs. Photon Design has been one of the earliest companies supporting such an approach with its PicWave tool. The idea is illustrated in Fig 13.

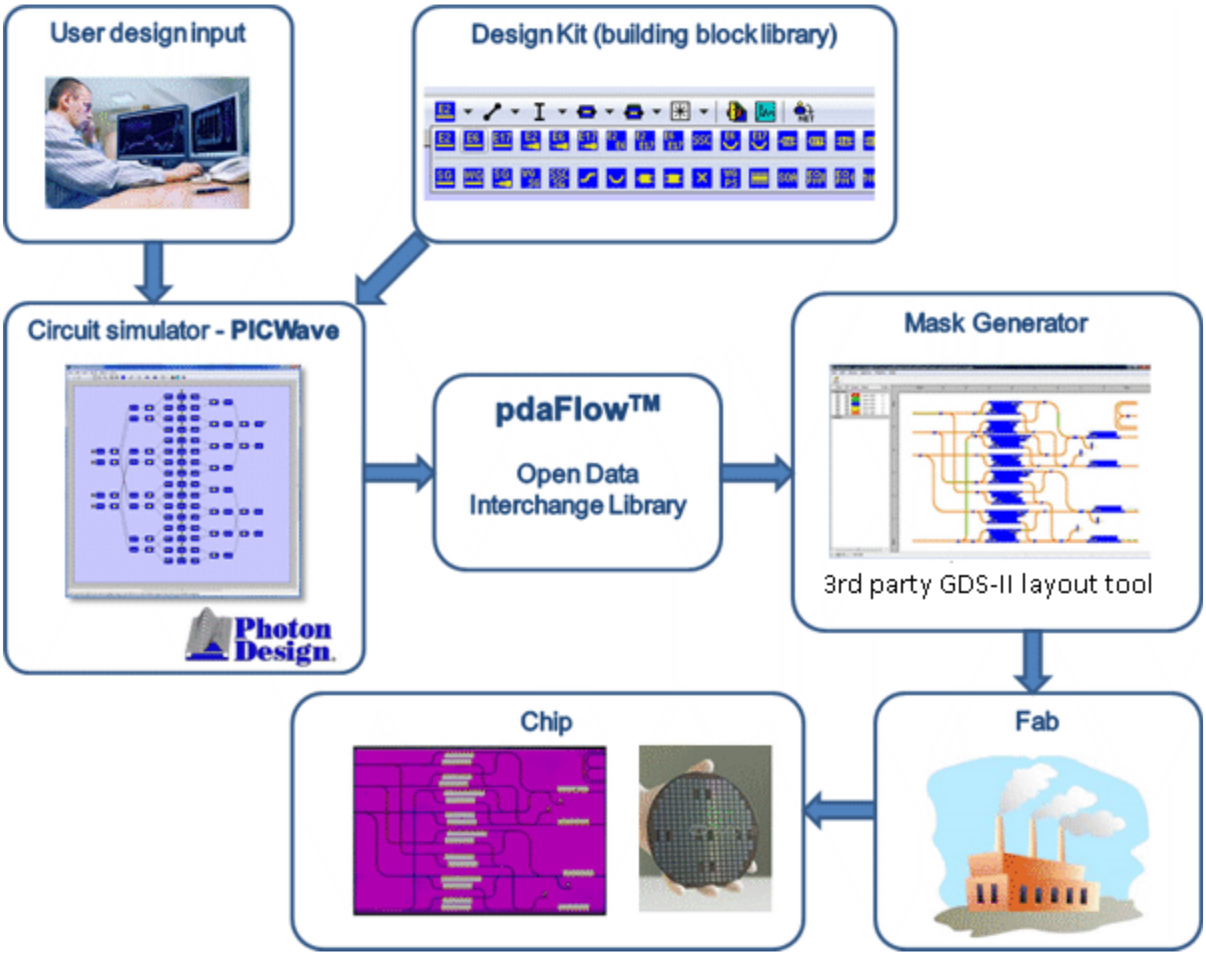


Fig 13. Illustrating the design of a PIC using a Design Kit. Experts at the foundry and tools vendor develop the Design Kit. The application designer can then use this kit assembling and testing a PIC design quickly.

Figure 13 illustrates a 4x4 optical cross-switch designed and simulated with PicWave then fabricated at a European InP foundry (HHI). PicWave is particularly suited to InP foundry support with some of the Worlds' advanced InP device models now accessible to even the smallest company via a design kit.

3 Summary

Photonics is evolving rapidly, promising to pervade every household, every PC in the next 10 years. This article has shown how the tools are now available to address most of the challenges that this evolution is likely to throw up. Mature CAD tools are now available to tackle even the most complex problems in photonics.

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[1] D.F.G. Gallagher "Eigenmode Expansion Methods for Simulation of Optical Propagation in Photonics - Pros and Cons", Proc. SPIE vol. 4987, p69-82, 2003.
[2] D.F.G. Gallagher "Photonic CAD matures", IEEE LEOS Newsletter, Vol. 22(1), pp. 8-14, 2008.