## Defining terms

**Active region (of a semiconductor laser):** the region into which electrons and holes are injected and in which light is confined to create the optimum conditions for light amplification by stimulated emission of photons.

**Erbium-doped fiber amplifier (EDFA):** a linear optical amplifier composed of an optical fiber doped with erbium ions. Energy is supplied to the erbium by injecting light at a wavelength of 980 nm or 1480 nm. The erbium ions then release their energy by stimulated emission, thereby causing amplification of signals around 1550 nm.

**Fiber dispersion:** the variation of the velocity of an optical signal with wavelength in an optical fiber.

**Photonics:** a name for technologies using photons (light particles) as the information bearer. It includes the areas of optoelectronics, electro-optics, fiber-optics, and lasers.

**Propagation delay:** the time taken for an optical signal to travel between two points (here across a section of the laser model).

**Scattering matrix:** a matrix describing the relationship between waves incident upon both sides of a network to those reflected out of the network.

**Single-mode laser:** a laser emitting a single wavelength of light, with other wavelengths being less than 1/10 000 of the power of the dominant wavelength. Modes refer to the electromagnetic resonances of the laser cavity at optical frequencies.

**Transfer matrix:** a matrix describing the relationship between leftward and rightward traveling waves at one side of a network with those at the other side. Here the matrix represents a vertical slice of a laser.

**Transmission line modeling (TLM):** a method of formulating algorithms for solving electromagnetic field problems using a mesh of transmission lines joined at scattering nodes. TLM relies on the equivalence between Maxwell's equations and the telegraph equations.

**software**

Powerful laser models in photonics system simulators are a vital step toward virtual optical benches for optimizing communication system design

# Computer-aided photonics design

Photonics—the technology of using particles of light as carriers of information—is catching on because of the advantages of optical fiber over copper cable for data transmission, and the use of optoelectronic techniques for sensing and instrumentation. Optical fibers capable of carrying data at rates exceeding a terabit per second ($10^{12}$ b/s), and also spanning distances of tens of thousands of kilometers without electronic signal regeneration, have been demonstrated—feats impossible with copper and microwave systems.

Initially, photonic systems were point to point, involving a light source, fiber, and a photodiode. But now, as data rates increase, photonic circuits for switching, data regeneration, and demultiplexing are becoming more urgently needed. Also, due to the use of wavelength-division multiplexing on fibers and wavelength routing in packet-switched networks, more complex devices, such as tunable lasers and amplifiers optimized for wavelength translation, are in demand.

Photonic circuits and systems generally have far fewer components than electronic circuits because the bandwidths of typical photonic components can reach terahertz, compared to tens of gigahertz for electronic components. However, the interactions of the components can be complex, being akin to analog electronics where intermodulation, feedback, reflections, resonances, and nonlinearities are important.

As a result of these interactions, the design of a photonic system can be a truly daunting task. How can a designer be certain that important interactions have not been overlooked and that the designed photonic system will not become yet another shining example of chaos theory?

In electronics, the designer can turn to a wide range of computer-aided design and engineering (CAD/CAE) tools for simulation and layout of circuits. These tools offer confidence in a design by predicting complex interactions of simple components; they have built-in knowledge of how systems and components work, and are able to predict interactions between the components by simulation.

What is available for simulating photonic and optoelectronic components and systems? Do tools exist to help the overworked designer in this area, and if so, have they the same features as electronics tools?

Some of these questions may be answered by reviewing the background of recent developments in photonic device and circuit simulation and by identifying the requirements of a generic photonic device, circuit, and systems simulator.

### The ideal simulator

When buying a CAD/CAE system for electronic systems, the prospective user expects more than just a drafting aid. Typically, built-in knowledge of the components' physical layout is expected to be included in a printed-circuit board design software package, as are timing analysis options in an integrated-circuit design package. Ideally, a designer expects the computer to divulge whether the design will work, and if not, why.

When considering photonic systems simulators, the user looks for accurate device and component models, into which parameters and operating conditions may be fed to produce outputs for analysis by instrumentation or to drive other models

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[Fig. 1]. If the device and component models are properly formulated, they embody many years of experience of the engineering community. Given an input, they will automatically search out the relevant theory of operation of the photonic device in question and provide an output.

Consequently, the circuit or system designer need not know about every laser phenomenon, but will be reminded of certain phenomena when the system is simulated. In fact, the package could be said to have encapsulated knowledge. Furthermore, its total knowledge is greater than the sum of the information it has about each device, because interactions between any combination of these components or devices can be predicted by simulation.

Encapsulated knowledge requires that the component models contain few assumptions, and that interfaces between them convey sufficient information. For generality, it is desirable that a simulator of photonic devices and systems:

• Cover all of the phenomena that could affect the performance of the overall circuit or system.
• Have compatible component models, allowing interconnections to be made for circuits or systems.
• Use bidirectional interfaces between components that pass sufficient information for all interactions.
• Include numerically efficient models, so that a wide optical bandwidth can be simulated over relatively long time periods.
• Include mechanisms for trading off accuracy for speed in the early stages of a design optimization.
• Contain large-signal nonlinear system models to study nonlinearities that are either detrimental (crosstalk and distortion, say) or useful (wavelength conversion and soliton transmission). In soliton transmission, nonlinearity is used to advantage to cancel out the pulse-spreading effect in optical fibers due to dispersion—variation of propagation velocity with wavelength (bluer colors travel faster than red).
• Optimize transmission bandwidth and distance against component complexity. For example, does the laser have to include a wavelength-stabilizing grating to reduce pulse spreading in the fiber due to dispersion?
• Optimize the design of the active device (the semiconductor laser, for example) to increase the photonic system's transmission distance, bandwidth, and signal integrity.

Most of the emphasis here will be on models for simulating semiconductor lasers. These are the most complex devices in a photonic simulation and, understandably, the most computationally costly.

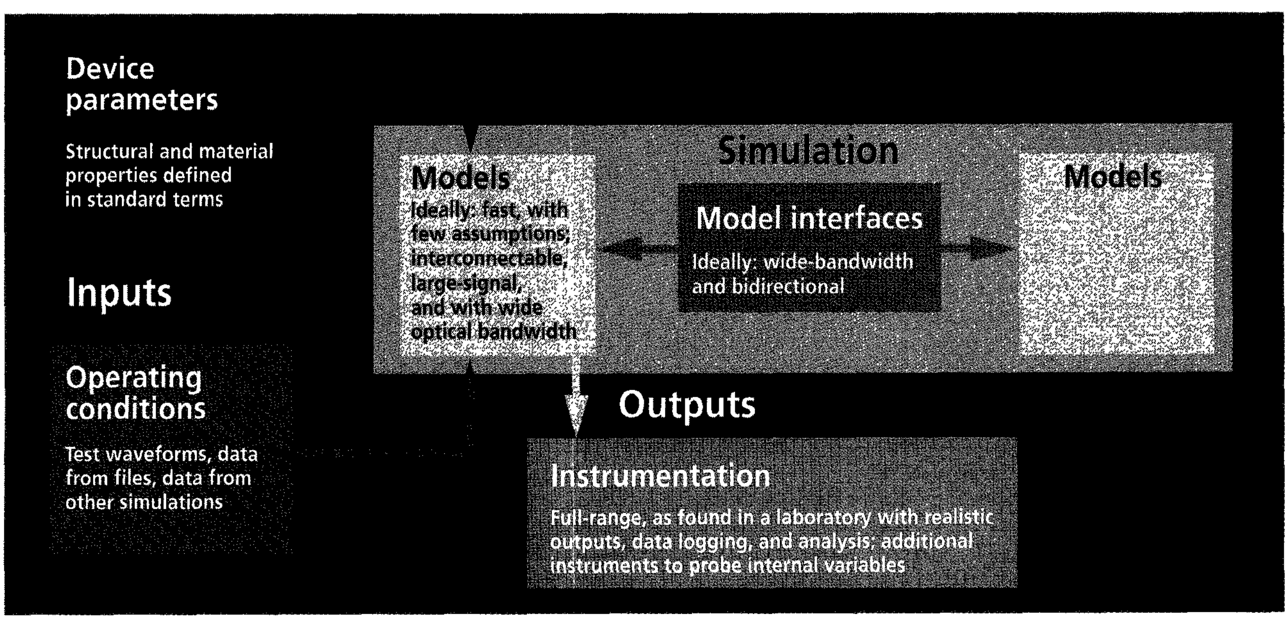
## Optics, carrier transport and more

Semiconductor lasers have an extra layer of complexity over electronic devices because optical waves have to be considered in addition to conventional currents and voltages. The dynamics of carrier transport are also more complex, although effective parameters can be used to represent some effects to achieve computational efficiency. What's more, the optical waves are at much higher frequencies than the electric signals, and have interactions over bandwidths of hundreds or thousands of gigahertz.

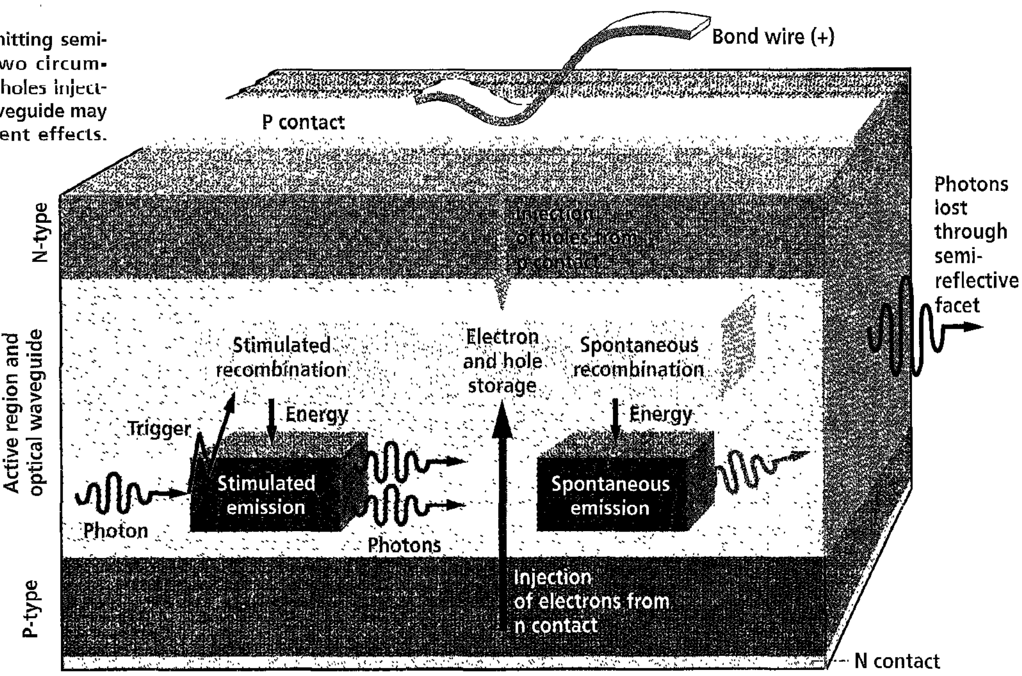
Most laser diodes have an optical waveguide grown in the plane of the semiconductor wafer. These are called edge-emitting lasers. Vertical-cavity surface-emitting lasers (VCSELs), however, emit photons perpendicular to the wafer. The focus in what follows will be on edge-emitting lasers, though the techniques can also be applied to VCSELs with additional computations for heating, wave-profiles, and current-flow.

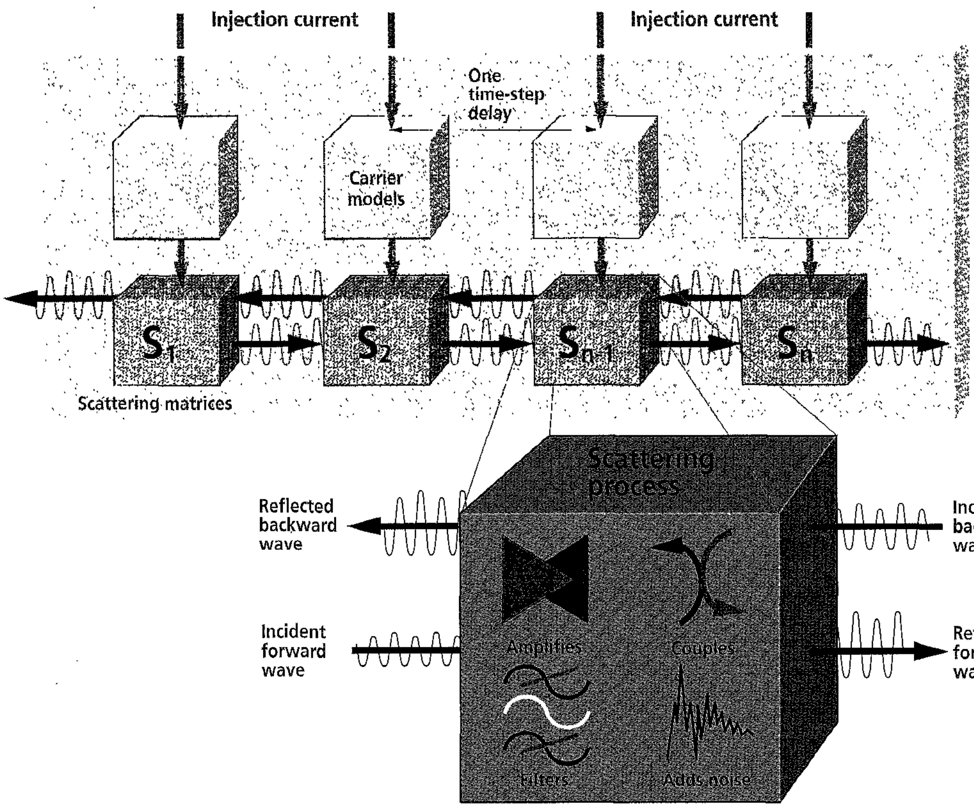
The simplest, and therefore the fastest, semiconductor laser models describe the optical waves as a photon population, averaged over the entire optical bandwidth and the entire optical cavity. Typical models include spontaneous and stimulated photon creation processes within the laser's active region [Fig 2]. In both cases, the energy comes from recombining an electron from the high-energy-level, conduction band with a hole in the low-energy, valence band. Spontaneous recombination emits a photon with random optical phase, direction, and polarization, and so light is emitted over a wide range of wavelengths. In stimulated recombination, an existing photon triggers the emission of another whose phase, direction, polarization, and wavelength are identical to its own.

**[1] An ideal photonics model includes comprehensive numerical models, interconnected with bidirectional interfaces. The model accepts such inputs as process device parameters and operating conditions to produce outputs that are monitored by realistic models of instrumentation.**



[2] This diagram of an edge-emitting semiconductor laser illustrates two circumstances in which electrons and holes injected into its active region and waveguide may recombine—with quite different effects. Spontaneous recombination broadens the lasing spectrum by emitting photons having random wavelengths, just as noise does in a conventional oscillator. Stimulated emission, on the other hand, elicits a narrow line width (optical bandwidth) from a laser oscillator; in the process, a photon population with a well-defined frequency is replenished with identical photons as it loses its members to the outside world. The carriers are injected into the active region by a voltage applied between the p and n contacts.




[3] In a transmission-line laser model, the cavity is divided into sections, each being represented by scattering matrices—$S_1$, $S_2$, and so on. These matrices take incoming (incident) waves and modify them to represent stimulated emission by gain, filtering, coupling due to index variations of the kind due to longitudinal gratings, and also noise from spontaneous emission. Outgoing (and reflected) waves are passed along transmission-line delays to the adjacent scattering matrices. Carrier models account for the populations of electrons and holes in each section.

The rate of stimulated emission depends on the number of photons already present, as well as on the number of electrons, while the spontaneous emission rate depends on the number of electrons alone. Equations for the rate of increase of electrons and photons can be formulated by using these rules, and by considering other mechanisms that change the electron and photon populations. Numerically integrating these rate equations will reveal the dynamics of the electron and photon populations. Dynamic fluctuations in the wavelength of the laser (assuming it oscillates in a single mode of the cavity) can be estimated from the electron population.

## Spectral simulation

For long-haul fiber communication systems that may extend over hundreds, or even thousands, of kilometers, a single-frequency laser is essential. For distances of more than a few tens of kilometers, multi-wavelength optical pulses will broaden extensively due to fiber dispersion. For this reason, a model that will identify multi-wavelength lasers, known as multi-mode lasers, is required.

Because these modes are at different wavelengths, their probabilities of stimulated emission, or gains, are likely to be a little different. During the turn-on of the laser, some modes will undergo more amplification than others, and the spectrum will narrow as it evolves. Multi-mode laser models usually track the photon population of each mode with a separate rate equation, and can even account for interaction between the modes due to intermodulation.

Rate-equation models are unable to cope with complex cavity structures, because they assume a set of modes (found by field-equation analysis of the cavity) and simply calculate the dynamics of each mode. If a laser is being designed to have a certain mode structure, they are of no help. Also, they ignore the spatial distributions of power and electrons along the laser.

In Fabry-Perot lasers, which are multimode, this power is reasonably homogeneous. In distributed-feedback (DFB) lasers, reflections are added along the laser to ensure lasing at a single wavelength (single mode). The optical power in a DFB laser can be highly inhomogeneous, leading to a spatially and time-dependent refractive index (because the index is dependent on the electron density), which can cause self-pulsations or promote multi-mode lasing.

Could a simple rate-equation model be used if it were known that the laser emitted only a single frequency, as a properly designed DFB laser does? Unfortunately not. Laser chirping is the change in wavelength with time, and is strong during pulsed operation of the laser. During a pulse (which could represent a "1" in a digital communications system), the lasing frequency will chirp over a span of tens of gigahertz. This chirping limits the transmission rate in currently installed optical fiber, again because of pulse spreading due to fiber dispersion.

Rate-equation models predict a different chirp waveform to that observed for DFB lasers, owing to a strong dependence of chirp on the local electron density along the device, rather than on the average electron density used in rate equation models. For this reason, models that split the laser cavity into sections are needed in order to consider the effect of each section on the optical waves passing through the sections.

## Scattering and transfer matrices

Transfer matrices (TMs) have been employed by many researchers to analyze the optical field within a DFB laser's cavity. Each TM represents a longitudinal slice of the laser, typically 10 μm wide, and the optical resonances, which may support lasing modes, can be identified by multiplying the matrices sequentially from right to left. Unfortunately, stimulated emission due to the lasing mode will perturb the carrier density, hence the refractive index along the cavity. So, as the optical power builds up, the cavity mode frequencies have to be recalculated.

An alternative is to use scattering matrices, which are closely related to transfer matrices. Scattering matrices take incoming (incident) waves and scatter them to produce outgoing (reflected) waves [Fig. 3]. After some delay, the reflected waves will impinge on adjacent scattering matrices, becoming incident waves.

If this delay is equal to the interval between iterations, all incident waves will arrive simultaneously, and the solution is simply to repeat the scattering operation at every matrix at every iteration. The delays between the matrices can be thought of as distortionless transmission lines. This technique, called transmission-line modeling (TLM), was originally developed to solve field equations.

TLM was first applied to lasers (hence TLLM, with the added L for lasers) in 1986 by this author while at the University of Nottingham. These models are solved in the time domain only, and the spectra can be found by Fourier transform techniques. A time-domain solution allows for simulation of such nonlinear effects as the mixing of optical frequencies in the laser, which broadens the spectra, an effect that occurs when the laser is pulsed on (from off) by a large current pulse.

Because the information flow in the model mimics the propagation of light along the laser cavity, the evolution of optical pulses shorter than the laser's length is accurately modeled. Thus, a simple change from a transfer matrix to a scatter-

# A software sampler

Several of the photonics simulation packages that are available include:

**BeamProp Version 2.0:** Research Software, 13 Lancaster Ave., Montrose, NY 10548; 914-734-2665; fax, 914-736-9823; Web site, http://www.rsoftinc.com. Software for the design and simulation of both optical waveguides and fiber-based photonic devices. Applications include the design of wavelength-division–multiplexed components, modulators, and switches. Simulation is based on two- or three-dimensional scalar, semi or full vector finite difference beam propagation. Graphical interface includes a computer-aided design layout system and automated parameter scanning, among other features.

**Comsis:** Ipsis, 3, Square du Chêne Rermain, F-35510 Cesson-Sévigné, France; (33+299) 27 53 27; fax, (33+299) 27 53 28; e-mail, support.technique@ipsis.galeode.fr. An interactive simulation package for analysis and design of communications systems. Its optical model library includes such elements as laser sources, optical amplifiers, fibers, and photodetectors.

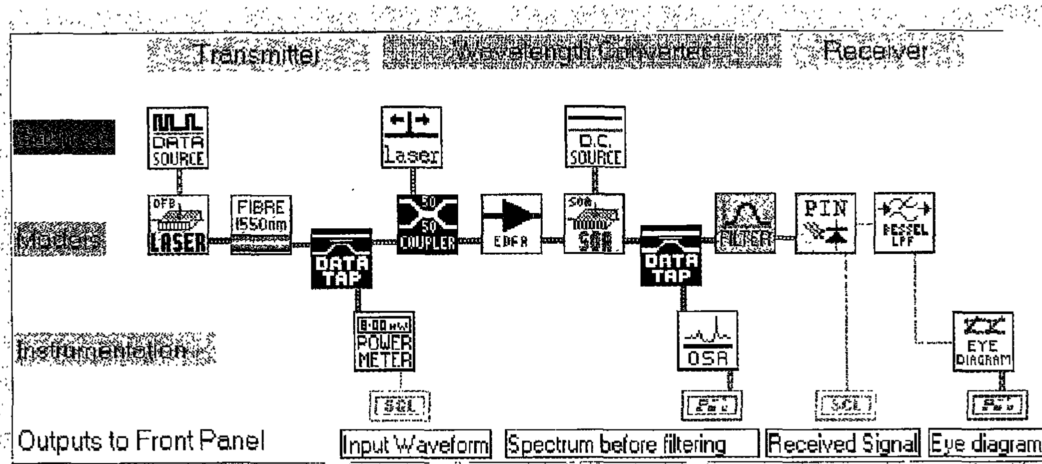
**i-Cladiss:** Photon Design, 86 Cortland Rd., Oxford, OX4 4JB, United Kingdom; (44+1865) 395 480; fax, (44+1865) 395 481; e-mail, info@photond.win-uk.net. A comprehensive laser diode model simulating the dc, am, fm, harmonic distortion, and time-domain characteristics of single and multi-section lasers and amplifiers. Part of a major European design project, the model incorporates most of the key physical processes affecting the device.

**Lastip, Dilas-II, PICS-3D:** Crosslight Software Inc., Box 27102, Gloucester, ON, K1J 9L9, Canada; 613-742-0786; fax, 613-742-7453, e-mail, crosslight@clark.net. Lastip is a two-dimensional laser simulator that includes detailed models of current flow, field distribution, and optical gain in quantum-well structures. Dilas-II is a model for longitudinal modes in Fabry Perot and distributed-feedback semiconductor lasers; it includes noise analysis. PICS-3D combines features of Lastip and Dilas-II for full three-dimensional modeling of complex structures.

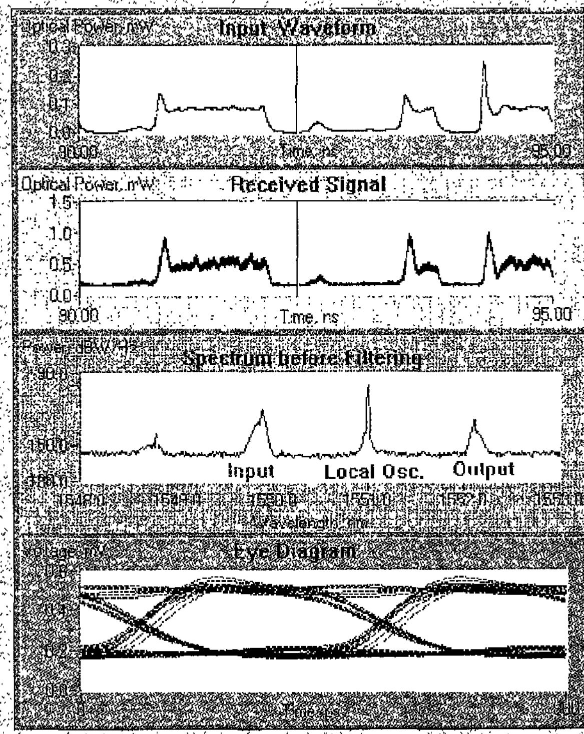
**Microwave Harmonica:** Compact Software, 210 McLean Blvd., Paterson, NJ 07504; 201-881-1200; fax -8361. A nonlinear RF and microwave circuit simulator. Includes optoelectronic element libraries of laser diodes, light-emitting diodes, optical fibers, attenuators, and photodetector diodes. Appropriate for designing microwave matching circuits between optoelectronic and microwave circuits, and between point-to-point microwave optical-fiber links. Factors such as return loss, gain compression, intermodulation, and efficiency can be calculated.

**Minilase II:** Computational Electronics Group at the Beckman Institute, University of Illinois, 405 North Mathews Ave., Urbana, IL 61801; 217-333-9734; fax, 217-244-4333. Minilase II is a semiconductor laser simulator that includes detailed models of carrier transport in quantum-well devices. It can be used to relate fundamental physical processes to the modulation response of lasers.

**Optoelectronic, Photonic, and Advanced Laser Simulator (OPALS):** Virtual Photonics Pty Ltd., Level 4, Walter Boas Building, University of Melbourne, Parkville, Victoria 3052, Australia; (61+3) 9344-7911; fax, (61+3) 9347-3414; e-mail, info@vp.com.au; Web site, http://www.vp.com.au. An icon-based simulator for devices, circuits, and systems. A simulation is constructed by linking models of photonic components that are customizable. The models are bidirectional, operate over a wide optical bandwidth, and include nonlinearities and noise. *—Ed.*




## Simulating a photonics system




Source: Virtual Photonics Pty Ltd

In the simulation of a wavelength converter using the opto-electronic, photonic, and advanced laser simulator from Virtual Photonics Pty. Ltd., the input test signal is generated using a single-mode distributed-feedback (DFB) laser driven by a pseudo-random data source at 2.5 Gb/s. The output of the laser propagates through an optical fiber. A data tap allows the user to monitor the input to the converter by using a 100-GHz power meter without affecting the signal level [see photo, above].

The signal from a second laser used as a local oscillator is combined with the input using a 50/50 coupler, and amplified by an erbium-doped fiber amplifier (EDFA). Next, the signal goes to a dc-powered semiconductor optical amplifier (SOA), with the nonlinearity for mixing between the optical input wavelengths, thereby yielding wavelength conversion. An optical spectrum analyzer (OSA) monitors the output spectrum. Subsequent optical filtering helps select the output wavelength. The filtered output is sent to a p-i-n photodiode with a bandwidth of 20 GHz, whose output is displayed directly. Further electrical filtering by a 1.75-GHz Bessel low-pass filter improves the signal-to-noise ratio. The electrical signal is then plotted as an eye diagram.

A digital sequence—0011100001011—representing an optical power waveform provides an input to the simulated wavelength converter [top waveform, right]. The (power) waveform received following the conversion [next waveform] is degraded from the shape of the original signal, as a result of noise in the amplifiers and the limited bandwidth of the tunable optical filter.

Using Fourier transform, the simulator calculates and displays the optical spectrum at the output of the semiconductor optical amplifier—an input wavelength at 1549.9 nm, the local oscillator signal at 1551.0 nm, and mixing products at 1548.8 nm (rejected) and 1552.1 nm (selected) [third waveform]. The eye diagram [bottom] indicates more noise on the 1 bits (0.5 mV) than on the 0 bits (0.2 mV), due to spontaneous emission from the semiconductor optical amplifier mixing with the required signal at the p-i-n photodiode. (This diode is a nonlinear device whose output current is proportional to the square of the combined electrical fields of its light inputs.) —A.J.L.

ing matrix notation yields many advantages, and the resulting efficiency of TLLM permits simulations over an optical bandwidth of several terahertz.

TLLMs are ideal for CAD systems as they can be connected to similar models to form a multi-section laser, circuit, or system. A TLLM follows the topology of a real laser, which may include several regions of different materials or several resonators coupled in line, making translation from a schematic diagram of a laser to a full simulation a trivial matter. What's more, the propagation delays between the regions are used advantageously to split a complex model into smaller models that are solved independently. This approach allows TLLMs to be tested independently against well-known analytical solutions or examples, and then interconnected with well-defined interfaces.

### 'Virtual' and real data compared

A laser model is only one of the components in a photonic circuits and systems simulator. Indeed, even for modeling devices, the user should be provided with an interface that has a set of driving sources, measuring instruments, and data analysis options. For circuits and systems models, all the standard components found in the laboratory and the field are required: couplers, fibers, attenuators, amplifiers, photodiodes, filters, fiber gratings, and delays.

The driving sources for the laser should include sine waves for pulse generation by gain-switching and mode-locking, pulse generators, and data generators. Instrumentation should include optical spectrum analyzers, RF spectrum analyzers, ultrafast oscilloscopes, power meters, autocorrelators, tunable sources, two-port analyzers, and interferometers for chirp measurement. Data analysis should allow jitter in amplitude and timing to be measured, and estimates of bit-error rates to be performed.

The interface should let the user enter a topology quickly and accurately, perhaps with a degree of on-line checking. Ideally, such parameters as drive currents and filter wavelengths should be alterable during a simulation, though programming efficiency may require that some parameters such as those describing the laser's structure, are fixed during a simulation run. As the outputs of the models are generated, they should be displayed.

This procedure is sometimes known as "real-time" simulation, although a nanosecond of laser time may require a few seconds to simulate, that is, it is not "real speed." Real-time simulation has an aesthetic appeal because the user can monitor progress, and is thus able to stop simulations, modify parameters, or continue the simulation, depending on the results as they appear.

One simulator of photonic devices, circuits, and systems that uses TLLMs at its heart, for example, is the optoelectronic, photonic, and advanced laser simulator (OPALS). Initially developed by a team led by Phil Gurney here at the Australian Photonics Cooperative Research Centre at the University of Melbourne in Parkville, Victoria, this simulator is now a product of Virtual Photonics Pty Ltd., also located at the university.

The simulator employs National Instrument's LabView as its user interface. Models of all common instrumentation and components are included as icons that can be wired together on a schematic. A key advantage of this simulator is that the interfaces between the icons pass data in both directions, so that feedback effects (such as reflections back into a laser, possibly leading to chaos) can be predicted. The bidirectional interfaces also enable the user to examine multi-cavity lasers by simply connecting together a series of single-cavity lasers (represented by icons).

Each icon can be "opened up" to reveal a control panel with a set of parameter controls. Not only does the simulation allow parameters to be changed while it is in progress, but the results can be compared with real data gathered from instrumentation by an IEEE-488 bus, permitting "real" and "virtual" experiments to be compared on the same screen.

For example, during a simulation of an all-optical wavelength converter, an optical signal from one wavelength channel is converted to another using the nonlinearity of a semiconductor optical amplifier as a mixer. The user may compare real data from such instruments as a power meter, an optical spectrum analyzer, and an oscilloscope—all connected to the PC and displayed using LabView—and get simulation results on display under LabView as well [see "Simulating a photonics system," p. 30].

The user can also study the effects of different parameters, such as amplifier length and bias level, on the output waveform by observing four results simultaneously on the screen—the input waveform that depicts the data stream, the power spectrum of the converter's output signal prior to optical filtering, the output waveform before electrical filtering, and a so-called "eye diagram," a commonly used display format for digital signals that highlights such phenomena as noise and jitter [screen photo, p. 30, and *IEEE Spectrum*, "Getting more out of eye diagrams," March, pp. 60–63].

This converter could be used in wavelength-division multiplexed (WDM) optical communications systems, in which separate carriers share the large bandwidth of an optical fiber.

Simulations such as this one help the user predict complex component interactions and study the effects of many parameters. The simulation time for this converter was 160 seconds per nanosecond of laser time using a 100-MHz 486-PC notebook, fast enough to allow many combinations of parameters to be assessed in a reasonable time. The simulation time is proportional to the square of the optical bandwidth, because the iteration time-step is in inverse proportion to the bandwidth, and the number of sections that the devices are divided into is in inverse proportion to the time-step. As can be seen from the spectrum in the screen photos shown on the preceding page, the frequency is continuous within the modeled bandwidth while the frequency resolution is set by the duration of the Fourier transforms used to analyze the signal.

## Next: optimization

Photonic computer-aided design should speed the acceptance of photonic solutions and help designers cope with the tremendous know-how needed in developing photonic systems. If photonic simulators can encapsulate enough of this knowledge, they will become as pervasive as electronic simulators. Once this happens, the costs of designing application-specific photonic devices, circuits, and systems will drop.

Since most of today's photonic systems simulators are limited by computer power, they must make some prior assumptions about the microscopic behavior of the device if a large system is to be modeled. This is analogous to electronic circuit simulators that use lumped parameters, rather than semiconductor device equations, for describing individual devices.

Future simulators may well incorporate greater detail into their models, allowing the waveguides to be designed, the current flow to be optimized, and the parameters to be extracted directly from material compositions, before dynamic simulations on complete systems are performed. Linking dynamic simulators to photonic IC layout packages will speed design, echoing the development of electronic CAD/CAE packages that lay out and simulate circuits entered from schematics. Tools for automatic optimization and sensitivity analysis should also be developed.

Fortunately, electronics has created the computer technology capable of performing complex simulation tasks. With this technology speeding up simulations, photonics should enjoy a rapid development in the years ahead. ◆

## To probe further

Discussions of recent progress in modeling photonic devices, along with many useful references, are included in the *Proceedings of the conference on Physics and Simulation of Optoelectronic Devices IV*, Photonics West 1996, San Jose, Calif. (Vol. 2693, SPIE—International Society for Optical Engineering). (SPIE originally stood for the Society of Photo-optical Instrumentation Engineers.)

Comparisons of and many references to laser models being developed in the European Union are included in "Comparison of different DFB laser models within the European COST-240 collaboration," by C. Morthier, R. Baets, et al. (COST240 Group), *IEE Proceedings on Optoelectronics*, 1994, Vol. 141, pp. 82–88.

Wavelength converters are discussed by M.A. Summerfield and R.S. Tucker in "Noise figure and conversion efficiency of four-wave mixing in semiconductor optical amplifiers," *Electronics Letters*, Vol. 31, 1995, pp. 1159–1160.

Adding knowledge bases to computer-aided design and engineering systems is discussed in "Smarter computer-aided design," by K.A. Reinschmidt and G.A. Finn, *IEEE Expert*, August 1994, pp. 50–55.

Vertical-cavity surface-emitting lasers are discussed in "A different mirror..." by Paul L. Gourley, Kevin L. Lear, and Richard P. Schneider Jr., *IEEE Spectrum*, August 1994, pp. 31–37.

Distributed-feedback lasers are discussed in "Single-frequency semiconductor lasers," by Trudy E. Bell, *Spectrum*, December 1983, pp. 38–45.

## About the author

Arthur James Lowery (SM) is an associate professor and reader in the department of electrical and electronic engineering, at the University of Melbourne, Australia, which is a member of the Australian Photonics Cooperative Research Centre. He is also a director of Virtual Photonics Pty Ltd., a company specializing in software for the photonics industry. Lowery was awarded the 1995 Australian Telecommunications and Electronics Research Board Medal for Outstanding Young Investigator.

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