Lasers & fibres

The success of optoelectronics in information technology will ultimately depend on the ability to make, and understand, smaller, cheaper and more reliable devices

Semiconductor microlasers

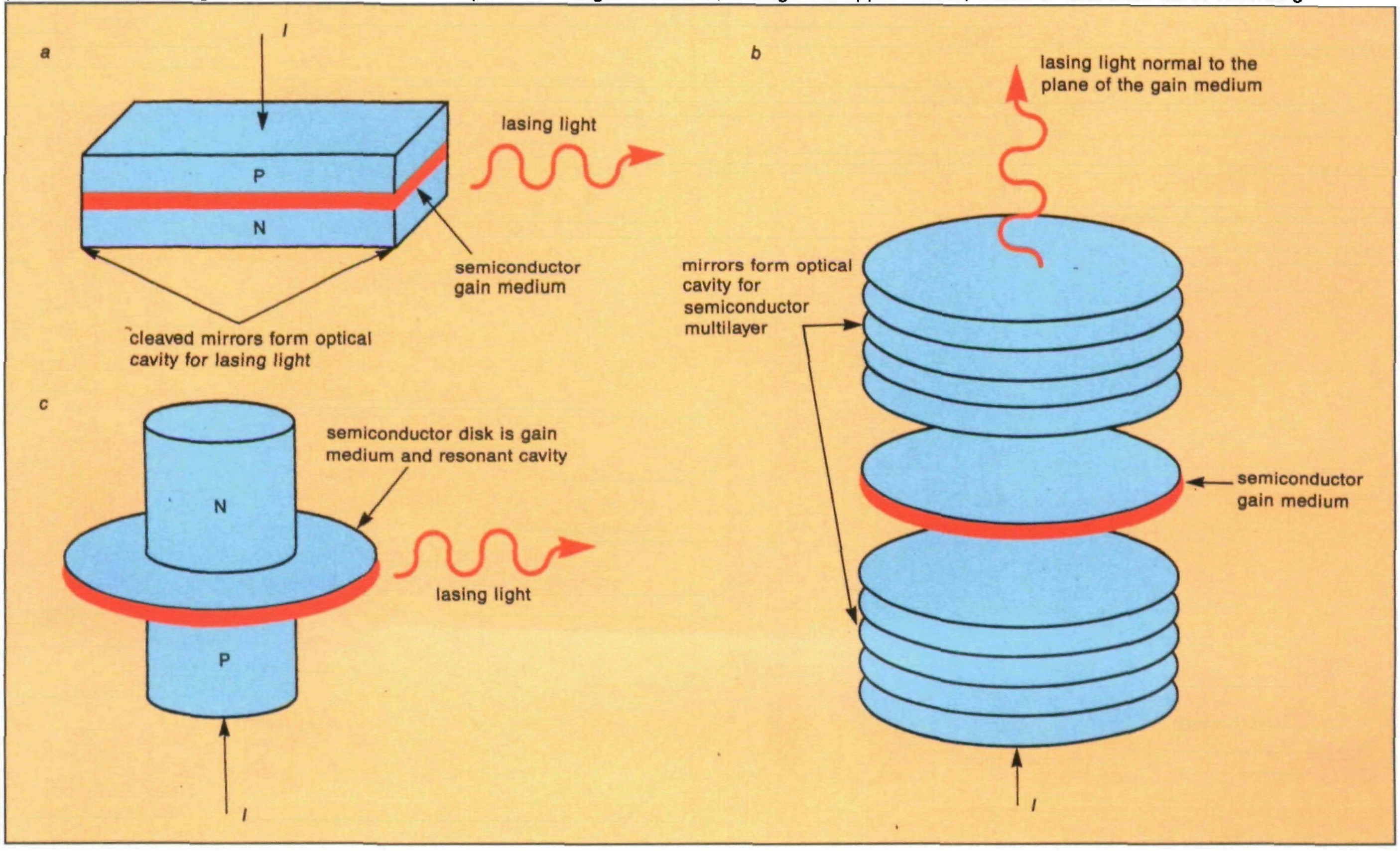
A F J LEVI

AS WE near the end of the 20th century, the need to construct machines which process and distribute large amounts of digital information appears to be increasing inexorably. In these machines the information must flow between and within various electronic processors and memories, as well as to and from input/output interfaces. Examples include the supermarket cash register, personal computers, databases and telephone switches. Demand for new, more powerful information technologies means that optoelectronic devices, such as the semiconductor laser diode, are playing an increasingly important role in system design.

Today, laser diodes are used as light sources in fibre-optic transmission systems capable of transporting many gigabits of information per second between cities, countries and continents. The power of these communication links, each of which transmits at data rates of around 2.5 gigabits per second (Gb s^{-1}), is symbolised by their ability to transmit all the words in all 30 volumes of the *Encyclopedia Britannica* (roughly 4.5×10^8 uncompressed 8-bit characters) in a data stream just a few seconds long.

Typically, high-data-rate fibre-optic links are used for long-distance telephone, computer and video traffic. Yet, even within this seemingly mature technology, new developments – such as ultra-high-data-rate telecommunications using solitons – may dramatically cheapen and increase the use of fibre-optic information pipelines. Some idea of this potential is given by the experimental results of Peter Andrekson who, while working with Anders Olsson

1 Schematic diagram showing the drive current, *I*, and laser emission from: (*a*) an edge-emitting Fabry–Perot laser diode; (*b*) a vertical-cavity surface-emitting laser (VCSEL); and (*c*) a microdisk laser. All three lasers work as a result of electrons and holes recombining in the gain medium to produce photons. In (*b*) the light is emitted normal to the plane of the gain medium, through the upper mirror, which is less than 100% reflecting



at AT&T Bell Laboratories in 1992, demonstrated 64 Gb s^{-1} soliton transmission over 14 km of optical fibre.

In the context of this evolving optoelectronic market, it is natural to explore the possibility that photonic devices will be used *within* information machines to transport data between electronic integrated circuits or, possibly, within purely photonic circuits. While there is no easy approach to all the issues arising from such general considerations, it is clear that any attempt to introduce optoelectronic devices into otherwise electronic systems presents significant challenges to both technology and physics.

If photonic integrated circuits and related structures are to emerge as a viable technology, it will be necessary to develop new classes of small, yet efficient, photonic devices. By analogy with their successful electronic counterparts, we might expect practical photonic microcircuits to combine low costs and power consumption with high optical confinement and efficiency. In addition, the light will mostly be generated and guided in the plane of the semiconductor substrate. Such devices will inevitably need to have submicron dimensions. Hence, the question whether it is physically possible to make efficient laser diodes with such dimensions.

Microlasers

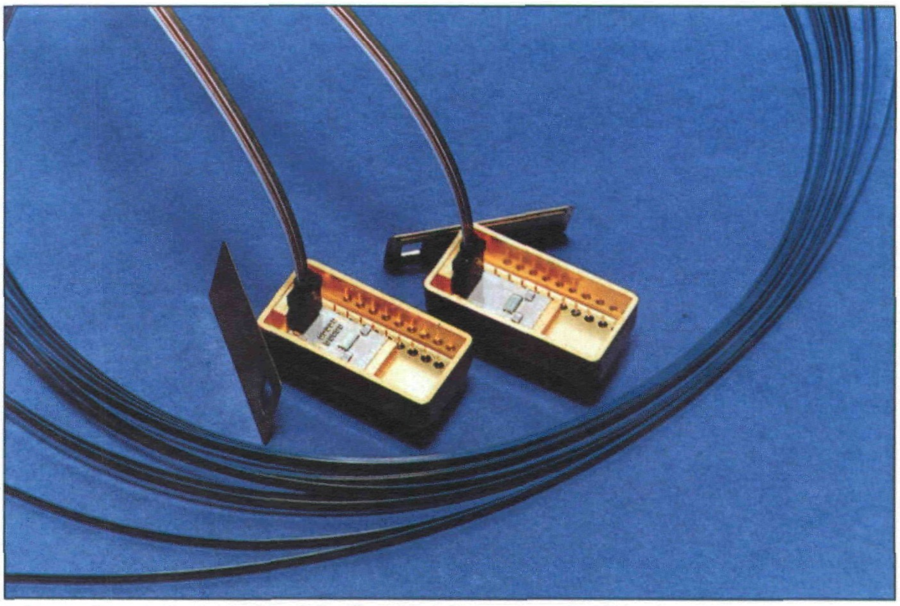
A conventional laser diode consists of an electrically driven semiconductor optical gain medium, such as indium gallium arsenide (InGaAs), placed within a resonant optical cavity. A simple Fabry–Perot resonator may be formed by cleaving the semiconductor crystal along two parallel planes – the cleaved faces of the crystal act as mirrors and the laser emits from the edge of the semiconductor gain region (figure 1*a*). When the diode is pumped electrically, the number of electrons (holes) injected into the conduction (valence) band of a direct band-gap semiconductor can be large enough to result in optical gain over a small spectral region corresponding to the energy difference, known as the band gap, between the top of the valence band and the bottom of the conduction band. This region is known as the band edge. Optical gain will overcome optical loss for the high-Q (low-loss) Fabry–Perot cavity mode nearest the peak in the gain spectrum first. Lasing emission should occur predominantly into this cavity mode because the cavity resonance ensures optical losses are low.

It is worth mentioning that edge-emitting lasers can use other types of optical resonator. For example, the semiconductor laser diodes developed for long-distance communications use more sophisticated distributed Bragg reflectors to form the resonator; the gain medium is typically ~300–500 μm long, 1 μm wide and 0.1 μm thick. Due to their relatively large size, these devices tend to be power-hungry and have threshold currents (the drive current at which lasing starts) greater than 10 mA. Stringent specifications and low production volumes result in high prices for these components. Companies such as Lasertron of Burlington, Massachusetts, have flourished by satisfying the specialised component needs of high-performance transmitters and receivers for long-distance fibre-optic communication systems.

However, the correct technological approach to achieving cheap, manufacturable microlasers for short-distance optical interconnects inside computers and other information-processing machines remains an unresolved issue.

Recognising the need for innovation, in the late 1970s Kenichi Iga and co-workers at the Tokyo Institute of Technology invented a new type of laser diode called the vertical-cavity surface-emitting laser (VCSEL – see "Surface-emitting lasers: a new breed" by Jack Jewell in *Physics World* July 1990 pages 28–30). Over the past 15 years VCSEL designs have been refined, and today dielectric mirror stacks (~1 μm thick) above and below a quantum well active region are used to form the resonant cavity. Laser emission is now from the surface (normal to the semiconductor substrate). Figure 1*b* shows a schematic diagram of a VCSEL. Lateral dimensions in the range 3–20 μm give a potentially superior optical beam profile for launching laser pulses directly into optical fibres without any need for a lens (unlike edge-emitting lasers), as well as threshold currents as low as 1 mA. While many practical problems still have to be solved, the initial results are encouraging enough for companies such as Bandgap Technology Corporation of Broomfield, Colorado, to develop VCSEL diode arrays for use in parallel optical data links (figure 2). For a review of VCSELs see Jewell in "Further reading".

More recently, Sam McCall and co-workers at AT&T Bell Laboratories suggested that very small laser diodes could be fabricated using a different type of resonant cavity in which light is much more tightly confined to the gain region and emission is in the plane of the semiconductor substrate. The device consists of an InGaAs/InGaAsP multiple quantum well structure formed into a 1.5–10 μm diameter disk approximately 0.1 μm thick. Electrical current and mechanical support is provided by n- and p-type indium phosphide structures above and below the disk (figure 1*c* and figure 3). Total internal reflection of photons travelling around the perimeter of the semiconductor disk results in high-Q "whispering-gallery" mode cavity resonances. The term whispering-gallery mode is taken from Lord Rayleigh's explanation of sound propagation in the dome of St Paul's Cathedral in London.



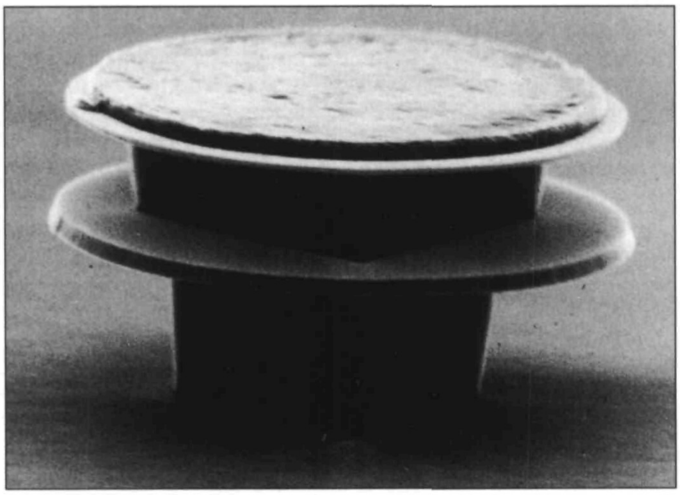
2 Transmitter and receiver modules for short-distance parallel fibre-optic data link. The transmitter uses a VCSEL diode array manufactured by Bandgap Technology Corporation of Broomfield, Colorado

In the microdisk laser, the low optical losses associated with whispering-gallery modes allow room-temperature lasing action with threshold currents of less than a milliamp, and improved designs should result in threshold currents as low as a few tens of microamps. Of course, one consequence of using very-high-Q resonators is that very little laser light radiates out into free space. However, it is possible to use output couplers which slightly spoil the Q and allow the light output to be increased, and redirected in or out of the substrate plane.

Model limits

A physical model which describes microlaser operation should be able to predict measurable static and dynamic quantities – such as the output intensity, frequency, linewidth and efficiency – as a function of measurable inputs such as the drive current, temperature and various parameters characterising the semiconductor. Over the years a number of essentially phenomenological models have been developed to describe the behaviour of conventional laser diodes.

It is remarkable that, while very small laser diodes have been fabricated, our understanding of how such devices work is manifestly inadequate. Much of what is interesting about microlasers cannot be modelled with the commonly used rate equations for carrier (electron and hole) and photon density in the device. In fact, efforts to explain microlaser effects with such a simplistic approach are somewhat pointless and bound to fail. Rather, it is necessary to examine every relevant aspect of the physics governing device operation before developing a new model for microlasers.



3 Scanning electron microscope image of an InGaAs/InGaAsP microdisk laser diode (diameter ~10 μm) similar to the device discussed in Levi *et al.* in "Further reading"

The spacing between the mirrors of a standard Fabry–Perot semiconductor laser diode is relatively large, and several hundred of the longitudinal cavity modes overlap the optical gain spectrum. It follows that only a small fraction ($\sim 10^{-4}$–10^{-5}) of spontaneous photon emission (which seeds the stimulated emission needed for lasing) feeds into any one longitudinal lasing mode. This, combined with the large difference between stimulated and spontaneous recombination rates, leads to an abrupt increase in laser output with drive current above threshold. However, below threshold there is also extra photon intensity in non-lasing cavity modes. On average, only a few of the several hundred cavity modes overlapping the gain spectrum actually lase.

There is a formal mathematical analogy between phase transitions in non-equilibrium statistical mechanics, as described by Landau and Ginzburg, and the statistics of the photon field around threshold. This allows us to describe all photons in cavity modes below threshold as (unsustainable) fluctuations. For example, below a critical (threshold) value of the pump rate, I_c , the average photon number of the lasing output, S, is the mean square fluctuation of the field amplitude. In this non-lasing regime the lasing output, S, is composed entirely of fluctuations. According to the Landau–Ginzburg theory, the average photon number should scale as the power law, $S \sim |I/I_c - 1|^{-\gamma}$, where $\gamma = 1$.

In a very small resonant cavity, such as those used in the new microlasers, it is possible that only one cavity mode overlaps the semiconductor's gain spectrum. In such a situation every spontaneous emission event fluctuates into the lasing mode and there is no abrupt increase in average laser output with which to define a laser threshold. Similarly, it is no longer possible to unambiguously define a threshold in terms of a phase transition or by calculating moments of the statistical distribution in the photon number. Clearly, the concept of a laser threshold, along with the Landau–Ginzburg theory of phase transitions, is no longer useful and a full quantum mechanical many-body description may become necessary. Unfortunately, progress towards a more complete picture has been slowed by the sheer enormity of the number of parameters needed to develop a realistic model (for more details see the book by Haken and articles by Lax and Carmichael in "Further reading").

It should be mentioned that fluctuations in photon number may also be driven directly by statistical fluctuations in the electron number. This may become important in microlasers which are so small they operate using only a few thousand electrons.

Of course, the previous discussion relates to only one aspect of the problem – defining a threshold. Unfortunately, this is overshadowed by the more fundamental concern of optical gain in a resonant cavity. Even after several decades of effort, physicists have failed to develop a satisfactory quantitative model of optical absorption and gain in *bulk* intrinsic semiconductors. Such a poor state of affairs is perhaps understandable when one begins to consider the complexity of the problem (for an overview see Haug and Koch in "Further reading").

Let us consider the special case when the electron distribution is in thermal equilibrium with the semiconductor lattice. Under low-drive-current conditions, the semiconductor's band-edge absorption spectrum (absorption/gain plotted as a function of energy or wavelength) shows strong conduction/valence band many-electron interaction effects in the form of spectrally sharp exciton features. Excitons are bound electron–hole pairs that move throughout the semiconductor and decay with a well defined half-life.

Under high drive current the semiconductor may contain $\sim 10^{18}$ cm^{-3} excess electrons and display optical gain over a small spectral range near the band edge, and absorption elsewhere. Electron interaction effects redistribute and broaden the spectral weight in the exciton features and a significant band tail – electron states in the otherwise forbidden gap between the conduction and valence bands – develops. The band gap itself is "renormalised" (made smaller) by the extra electrons which screen the interactions that initially set up the gap. Even if many-electron interaction effects could be evaluated beyond the random-phase mean-field approximation and the band tails could be explained quantitatively, we would still be limited to the case of thermal equilibrium.

However, it seems unlikely that the electron distribution in a microlaser is in thermal equilibrium with the semiconductor lattice anyway. The reason for this is that the calculated timescales for various optical and electronic relaxation processes in microlasers are comparable. For example, a microlaser of radius 1 μm, lasing at 1.5 μm, has a calculated cavity round-trip time of 40 fs, a cavity photon lifetime of 150 fs, and an electron–electron scattering "rate" in the 100 fs range. Under these conditions it is possible that the electron–hole recombination that leads to lasing will remove electrons from the system too quickly for the electron distribution to equilibrate. If this happens there will be a reduction in the number of electrons able to participate in optical transitions at the lasing frequency. The resultant "spectral hole burning" in the electron distribution reduces spontaneous emission into the lasing mode and modifies both the intensity and spectral purity of the microlaser output (see Henneburger *et al.* in "Further reading"). However, in practice, except for devices with a disk radius less than 1 μm, these effects are somewhat masked by the spatial diffusion of charge carriers from regions of low light intensity elsewhere in the microlaser.

The short and comparable characteristic timescales for cavity round-trip time, photon lifetime and electron-scattering rate in microlasers also raise the interesting issue of distinguishing between optical and electronic processes on short timescales. Indeed, in quantum electrodynamics, electron scattering is mediated via the emission and absorption of a photon, so on very short timescales one ultimately cannot distinguish between optical and electronic phenomena.

However, despite the problems in developing meaningful models to describe microcavity lasers, researchers have still been able to build microlasers that work and are looking for applications for this new generation of semiconductor laser.

Towards applications

An engineer designing a high-performance information system is not usually interested in details of how a device works. What is important is the cost–performance benefit of embedding a given module in a host system. In practice, the engineer is concerned with apparently mundane issues such as reliability, size, weight, power dissipation, speed and, very importantly, the absolute as well as the relative cost of any module.

For example, if microlasers are to be used for parallel optical data links similar to the one shown in figure 2, it is important that the module does not generate more than 0.5 W cm^{-2} in heat. Clearly, any such specification impacts on module size and packaging as well as the device performance. It follows that microlasers used for this application must have a very high absolute efficiency and that the so-called "wall plug efficiency" of the device should be as close to 100% as possible to avoid a significant overall system penalty.

Satisfying engineering requirements, such as those outlined above, will determine whether microlasers or any other optoelectronic device are destined to have significant commercial impact. Of course, our initial premise was that microlasers would find a role enhancing data transport and improving the performance of otherwise electronic information machines. Indeed, it is likely that microlasers will first be used for parallel optical data links. Other applications, in particular in the man–machine interfaces for such machines – scanners, printers and displays etc – are also being investigated.

Further reading

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A F J Levi is in the Department of Electrical Engineering and Electrophysics, University of Southern California, Los Angeles, CA 90089-1112, USA