A different mirror...

... grown, not cleft, eases the fabrication of semiconductor lasers and permits dense, two-dimensional arrays of diodes emitting round beams of light

Semiconductor laser diode technology has at last gone beyond the edge emission of light. In that invention of the early 1960s, photons shoot out of one edge of the semiconductor wafer after rebounding off mirrors that have been literally cleaved out of the crystalline substrate. In the new surface-emitting laser, though, photons bounce vertically between mirrors grown into the structure, and then shoot straight up (or down) from the wafer's surface. Those differences seem simple, but their potential consequences for manufacturing efficiency and new applications are tremendous.

Most critically, laser devices that emit light from their upper surface can be fabricated side by side on a wafer in vast numbers. Tens of millions can fit on a 100-millimeter-diameter wafer. Packing them in so densely enhances manufacturing efficiency. Even more important, the way they are made means they can be integrated on chip with transistors and other devices. There is no need to wire each of them individually to a circuit, as is done with edge-emitters, and they can even be optically linked to overhead elements.

Coupling efficiency also benefits from a surface-emitting geometry. The beam of light that issues from an edge-emitter, typically through a 1-by-2-μm aperture, is usually both elliptical and divergent—not at all the round, collimated beam that couples its entire energy into an optical fiber. In contrast, the surface-emitter aperture can be shaped to give the beam the ideal circular cross section and its diameter can be made large enough, at 5 μm, to minimize the divergence of the light rays.

Last, if left attached together on the wafer, surface-emitting lasers can form a two-dimensional array whose power and direction can be controlled. Pulsed power output of over 1 W has been demonstrated from a single array. Edge-emitters have delivered 10 times that much, but their geometry restricts them to one-dimensional arrays.

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To be sure, engineering hurdles still loom for surface-emitting lasers. The biggest is the substantial elimination of the heat from the light generation process. The other problems that must be resolved include controlling the light's polarization and delivering the power in one mode. But since potential applications range over optical-fiber communications, printing and scanning, two-dimensional image recognition, and computing, the devices are moving rapidly from research into manufacturing.

ATOMIC LAYERING. The surface-emitting laser's entire structure—mirrors and all—is built up by "spray painting" crystalline layers onto a substrate with atomic precision. By means of techniques such as molecular beam epitaxy and metal-organic vapor phase epitaxy, hundreds of layers of semiconductor materials can be grown one on top of the other. By mixing and matching the materials to create "designer" alloys, it is possible to grow a crystalline structure with all the electrical and optical properties desired for its various parts.

This method of tailoring semiconductor structures is called bandgap engineering [see "Quantum-tailored solid-state devices," by Timothy J. Drummond, Paul L. Gourley, and Thomas E. Zipperian, *IEEE Spectrum*,, June 1988, pp. 33–37]. In essence, thin layers are used to confine electrons and holes, while thicker layers serve as mirrors or waveguides to confine photons. "Thin" is about 10 nm, and "thicker," about 100 nm.

After these layers are grown uniformly across the full wafer, the next stage is to demarcate individual laser devices with such standard fabrication processes as ion implantation or plasma etching. They may be either separated for individual packaging or left joined together to form an array.

In surface-emitters, as with the edge-emitters, most of the pioneering work has been done with heterostructures of indium gallium arsenide and aluminum gallium arsenide alloys. Those III-V materials are ideal for complex surface-emitter devices. The crystal lattice of AlGaAs matches the spacing of the lattice of gallium arsenide substrates, so it can be grown epitaxially on GaAs wafers without fear of crystal defects and dislocations. Although InGaAs materials are not naturally lattice-matched, they can be grown on GaAs substrates if the layers are kept thin—and the elastic strain imparted to the thin layers has beneficial electronic properties. With *in situ* diagnostics, tolerances can be tightly controlled, and processing technologies such as ion implantation and etching are well understood. Finally, III-V heterostructures give laser diodes their lowest lasing thresholds and best temperature characteristics.

STRUCTURAL DIFFERENCE. In the surface-emitter, the semiconductor laser structure is swiveled by 90 degrees from the orien-

Defining terms

Band gap energy: the minimum energy required to break a valence electron from a crystal bond and set it loose in the crystal lattice as a mobile carrier.

Edge-emitting laser: the conventional semiconductor laser, in which the gain medium is grown epitaxially on a substrate and the two mirrors are formed by cleaving the resulting structure to expose reflective crystal facets. Light generated in the gain medium bounces horizontally between the facet mirrors (there is usually some lateral confinement), and some leaks out through one mirror to become the laser beam.

Epitaxy: the growth of crystal by depositing atoms on a substrate a single layer at a time by techniques employing molecular beams or gaseous chemicals.

Index of refraction: the ratio of the speed of light in a vacuum to its speed in a material.

Longitudinal optical modes: discrete optical resonances occurring in a semiconductor laser when twice the cavity length (distance between mirrors) corresponds to an exact multiple of the photon wavelength.

Quantum well: a thin layer of material of comparatively narrow band gap sandwiched between wider–band-gap layers for the purpose of trapping mobile carriers and confining them quantum-mechanically.

Vertical-cavity surface-emitting laser: a solid-state laser in which the two mirrors as well as the intervening gain region are grown epitaxially on a semiconductor substrate. Light generated in the gain region bounces vertically between the mirrors, and some leaks through the top surface mirror to form the emitted beam.

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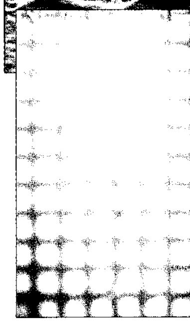
tation of a cleaved-cavity edge-emitter. The laser light does not travel horizontally within a single layer inside the wafer, but instead bounces vertically through the epitaxial layers between mirrors grown above and below the active layer. Because the active layer is only 10 μm thick, the length of the cavity between the mirrors is less than 10 μm—extremely short in comparison with the 100 μm or more of the edge-emitter's cavity.

The mirrors in a surface-emitter are grown into the laser structure itself. Each is composed of paired layers of two different materials, such as GaAs and AlAs: one material has a high index of refraction and the other a low index. (The index of refraction is the ratio of the speed of light in a vacuum to the speed of light in the material.) Because the light waves from successive layers interfere constructively, together, the pairs of layers can reflect more than 99 percent of the photons at the laser's emission wavelength.

The mirrors are known as quarter-wave stacks because each layer's thickness is equal to one-quarter of the wavelength of the light inside the material. The wavelength there is shorter than it is in a vacuum by a ratio equal to the refractive index. For example, the refractive indices of GaAs and AlAs are 3.5 and 2.9, respectively, at the emission wavelength of 980 nm, so that the respective layers need to be 70 nm and 84 nm thick to create an effective mirror.

On the top surface of the surface-emitter and the underside of the substrate, metal is deposited to form electronic contacts. A circular aperture is left in one contact as an exit for the laser light. When a voltage is applied to the contacts, electrons and holes are injected through the opposing mirrors and collect in the laser's active region (or cavity). There they are quantum-mechanically trapped by quantum wells—thin layers of material in which the electrons and holes have lower potential energy than in the surrounding material.

An electron and hole from the collections in the quantum wells can recombine at a random time to generate a photon but at an energy just too low for it to be absorbed in the material above and below the quantum wells. The quarter-wave mirrors reflect many of those photons back to the quantum well. Sometimes the photon is reabsorbed by the well, in which case it is converted into a new electron and hole. But if enough current has been pushed through the device to create an accumulation of electrons and holes in the quantum wells, the photon is not absorbed and converted. On the contrary, the quantum wells become transparent and the photon can bounce back and forth between the mirrors hundreds of times before escaping. In fact, the photon is likely to stimulate a new electron and hole to recombine, issuing a new photon. The photon population in the active region multiplies rapidly, and some of the photons leak out through the circular aperture in the contact on one mirror, producing an intense beam of coherent light.



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In this scanning electron micrograph, the "checkerboard" is in actuality a two-dimensional phased-locked array of vertical-cavity surface-emitting lasers. Molecular beam epitaxy was employed to grow the semiconductor wafer, complete with mirrors [light and dark stripes], and the result was topped by a thick phase-shift layer [solid light layer]. Then reactive ion beam etching was used to define each laser individually as a square, measuring 5 μm on a side, and the thick phase-shift layer was etched off the top of every other laser in the array. The inset is an optical micrograph of light emitted from the operating array.

A COMPARATIVE CINCH. With today's precise epitaxial technology, surface-emitters are expected to be much faster and simpler to make in high volume than conventional edge-emitting lasers can be. They need less special handling, above all because the mirrors are an integral part of the structure. (In contrast, the cleaved-facet mirrors of advanced edge-emitters may have to be coated or ion-milled, or gratings may have to be formed by laborious etching and regrowing.)

Thanks to its built-in mirrors, each surface-emitter can also be conveniently screened at the wafer level, before being separated. Since wafer-level testing identifies defective devices before packaging, only good ones are packaged and costs are again reduced. In contrast, a wafer of edge-emitters must be cleaved at least into separate laser bars—effectively one-dimensional arrays—to create the mirrors before the devices can be tested. In some cases, edge-emitting lasers must even be packaged to provide sufficient heat-sinking before they can be qualified at full power, and packaging is one of the principal costs of laser diode manufacture.

Packaging itself is often simpler for a surface-emission geometry. The output facet of an edge-emitting diode must be precisely aligned to the edge of its heat sink so that the heat sink does not obscure the output beam. But since surface-emitters emit light perpendicular to the plane of the wafer and away from the heat sink, their alignment tolerances can be much looser.

In general, semiconductor lasers are the most efficient of all lasers at converting input electric into output optical power. While helium-neon gas lasers of the type used in supermarket bar-code scanners are approximately 0.01 percent efficient, commercial laser diodes are 30 percent efficient or better.

One serious obstacle to high efficiency in surface-emitters, however, is high series resistance to the charge carriers (electrons and holes) transported through the laser mirrors. The high resistance reduces the laser's efficiency and generates unwanted heat, which limits the number of devices that can be integrated onto a chip.

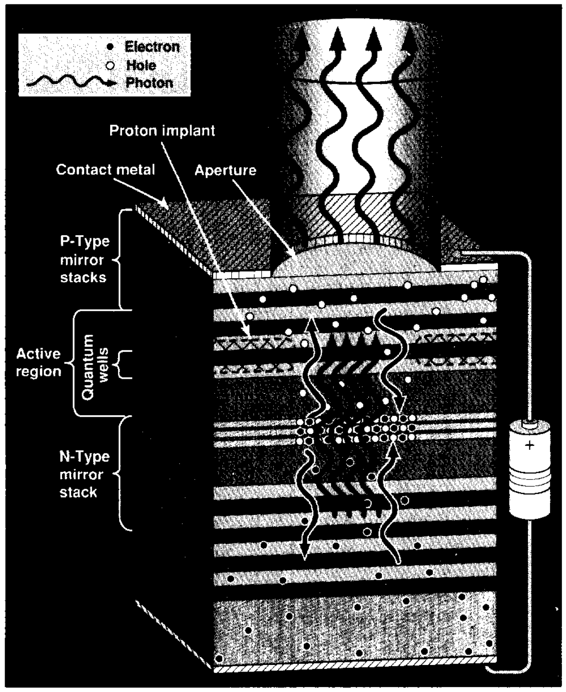
ROLE CONFLICT. Each quarter-wave stack in fact serves two functions: as a highly reflecting mirror for the photons, and as a current path for the electrons and holes. Choosing mirror materials for these two purposes is a balancing act. Material combinations with the largest possible difference in refractive indices make the best mirrors, since they give large reflections at each interface and so require fewer interfaces. For physical reasons, indices of refraction and band gap energy are inversely correlated, so material pairs with big changes in index also have big changes in band gap energy.

When the adjacent materials had very different band gap energies, the electrons and holes were compelled to "jump" up from the low-energy material to the high-energy material. Consequently, while materials with a large index difference yielded highly reflective mirrors, the concomitant changes in band gap energy between the layers were less than helpful, for they represented a series of large energy barriers that the carriers had to surmount as they moved from one mirror layer to the next.

That impediment to carrier flow was evidenced in high resistances, which increased the voltage drop and lowered the power conversion efficiency. The first surface-emitters as a result had efficiencies of only a few percent as well as threshold voltages of 3 V or higher. The wasted power, worse yet, was not lost; instead it went into heating the laser device, shortening its lifetime and limiting the number that could be joined into a two-dimensional array.

Many approaches have been used to decrease the series resistance of the mirrors while maintaining their high reflectivity. They have for the most part aimed at smoothing the change in bandgap energy by grading the composition of the mirror layers. This works well because electrons and holes have wavelengths (1 to 10 nm) that are much shorter than the optical wavelengths (about 300 nm) within the materials. In other words, grading the transitions between the materials eases the motion of the charge carriers on the scale of the carrier wavelengths while at the same time retaining the large differences in refractive index and the high degree of reflectivity at the photon's wavelength.

Grading approaches developed by one of the authors (Lear) at Sandia National Laboratories in New Mexico and by Larry Coldren and his colleagues at the University of California at Santa Barbara have been tolerably successful. They have lowered the resistance of quarter-wave mirrors enough to yield surface-emitter threshold voltages of less than 1.5 V and devices with efficiencies of 21 percent. Overall operating efficiencies are now within a factor of three of the best conventional edge-emitting lasers.



The mirrors of a vertical-cavity surface-emitting laser are paired layers of semiconductor materials, which together reflect more than 99 percent of photons at the lasing wavelength. The active region sandwiched between the mirrors includes several quantum wells—ultrathin layers that trap electrons [dots] and holes [open circles] injected from metal contacts applied to the substrate and top mirror. In the quantum wells the carriers recombine to produce photons [wavy arrows]. Photons of the right wavelength multiply as they bounce between the mirrors. Some of the photons leak out of the top mirror through an aperture defined in the top metal contact to produce an intense beam of coherent light.

In addition, Jack Jewell of Photonics Research Inc., Broomfield, Colo., and his colleagues have demonstrated a low-voltage vertical-cavity method that allows the carriers to bypass the mirrors altogether. Their design is similar to one pioneered by Kenichi Iga and his colleagues at the Tokyo Institute of Technology for indium-phosphide–based surface-emitting lasers. They inject current into the active region from the sides of the device, underneath mirrors that can even be made from insulating materials and that can be applied like coatings instead of being grown epitaxially. Although such an approach offers flexibility, it as yet does not offer the same performance as devices based on epitaxially layered conducting mirrors.

GAIN IN GAIN. The active region has also benefited from bandgap engineering. The laser's gain can be increased by a phenomenon known as periodic gain—essentially, pumping the optical standing wave at the wave crests. In surface-emitters, periodic gain can be realized by growing quantum wells at positions that coincide with the antinodes in the optical standing wave. The lasing wavelength is thus stabilized by being phase-locked to the gain regions. Moreover, the gain material in the active region is more effectively utilized as a source of electrons and holes that recombine to create photons in the lasing mode. Further evidence suggests that periodic gain can enhance spontaneous emission, which starts the lasing process.

Another means of increasing the laser's efficiency is to lard the active regions with thin layers whose crystal lattices are mismatched just enough to give rise to elastic strain. Holes in strained layers move more easily to match the motion of electrons. Consequently, the threshold current for lasing is reduced, heating effects are minimized, and the laser lifetime is extended.

As a bonus, strained-layer quantum wells are ideally suited to periodic gain. Strained layers can be kept thin (about 5 nm) and be spaced wide apart (130 nm), a configuration that prevents the strain from dislocating the crystal at various spots. Strain in addition flattens the gain spectrum, making the laser less sensitive to changes in ambient temperature.

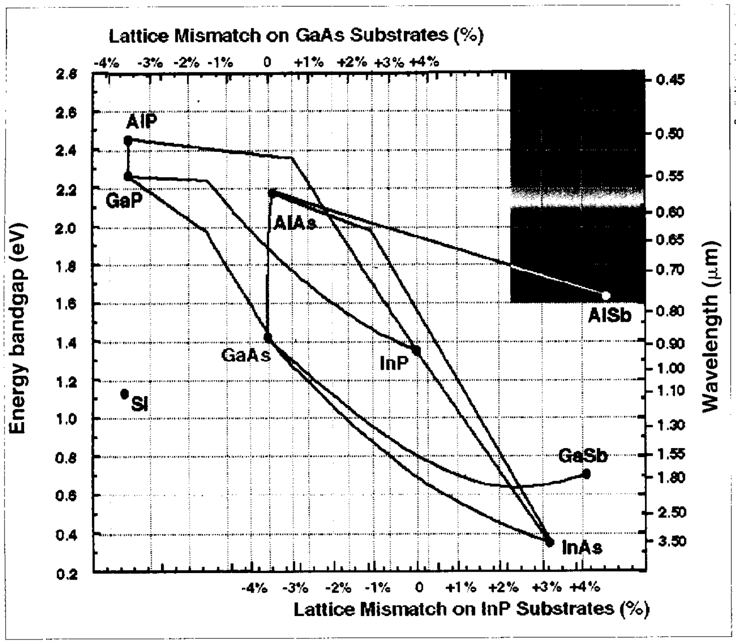
ULTRASHORT CAVITY. In a typical surface-emitter laser design, the space between the two mirrors is only 1 to 2 μm high. So very short a cavity has a profound effect on temperature and switching characteristics. The energy separation of the longitudinal optical modes (or primary lasing wavelengths) is inversely proportional to the cavity length. Accordingly, the modes are separated by approximately 0.1 electron volt, corresponding to a wavelength of about 100 nm.

A 0.1-eV separation is wider than the spectrum of gain required for light amplification. It therefore follows that in a surface-emitting laser, only one longitudinal mode should lase. (In an edge-emitter, however, many longitudinal modes will lase if they are not suppressed [see "Single-frequency semiconductor lasers," *Spectrum*, December 1983, pp. 38–45].) The surface-emitter operates most efficiently when the wavelength of its one longitudinal mode and the peak of the gain spectra are roughly aligned under operating conditions.

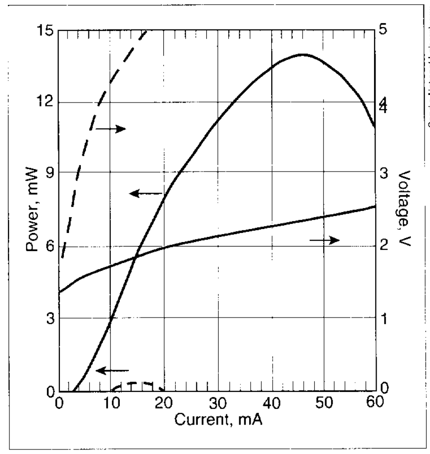
Moderate changes in temperature due to the laser's self-heating or to environmental heating will alter the alignment, but will not substantially change the laser output if the gain spectrum is broad enough. And in fact, the laser can be so designed that optimum alignment occurs near the highest specified operating temperature. The improved alignment then compensates for decreased gain at high temperature. In this way, a nearly constant operating current can be maintained over a wide range of temperatures (approximately 100 K). Such a result has not been achieved with conventional edge-emitting lasers; the reason is that their wavelength hops to match the peak of the gain spectrum, and the peak's height decreases with temperature.

A laser's stability is related to the cavity lifetime—that is, the average time a photon remains in the cavity. For stable lasing plus optimum output efficiency, the mirrors have to reflect enough light to sustain the lasing process, but leak enough light to maintain a strong output beam.

The laser's switching speed is also related to cavity lifetime, in inverse proportion. Adding to the cavity length and increasing the mirror reflectivity extend the



Band gap energy—which corresponds to emission wavelength [vertical axes, above]—depends on the composition of the semiconductor alloy. Few III-V semiconductor alloys have lattice spacing that matches the lattice spacing of gallium arsenide [top horizontal axis] or indium phosphide [bottom horizontal axis], the two most common III-V substrate materials. The solid lines represent continuous ternary (three-element) alloy compositions that connect points corresponding to binary compositions. For example, the line linking aluminum arsenide and gallium arsenide represents alloys of AlGaAs—used for most vertical-cavity lasers. To emit in the visible spectrum, however, phosphorus-based materials are needed. The band gap energy of silicon, not used for surface-emitting lasers, is shown for reference.



The performance of surface-emitting lasers has been improved dramatically by reducing the resistance of their mirrors. For two different lasers, the graph above plots the intensity of light [red] and the voltage drop [blue] as functions of the drive current. The lasers had a similar structure, except that the energy barriers between the layers in the mirrors of the newer devices [solid lines] were not as abrupt as those of the older ones [dashed lines]. The effect of those graded barriers in the new lasers was to reduce the voltage drop and associated joule heating in the mirrors as current was driven through them. As a result, each newer laser could work to higher currents and output powers than its predecessor. [The arrows in the diagram point to the vertical axis to which each curve is referred.]

cavity lifetime. For a cavity 2 μm long and with a mirror loss of 1.5 percent, lifetime is 5 picoseconds. Thus, the laser's intrinsic frequency response is up to 200 GHz. Other factors affecting laser switching speed include the collection of carriers in the quantum wells, the carrier concentration in the wells, and optical loss mechanisms. To date, parasitic elements have limited the response of surface-emitters to 14 GHz.

PLANAR ARRAYS. Perhaps the crowning glory of surface-emitters is their capacity for integration *en masse* into two-dimensional arrays. Since the placement of individual lasers on a wafer can be defined almost at will by standard microlithographic processing, designers have plenty of freedom to shape the light beam in the far field, remote from the wafer surface.

If dispersed on the wafer, the surface-emitters can be addressed either independently or as a matrix. If crowded together, they can be coupled in a phase-locked array. When phase-locked, all the lasers in the array operate in unison to create a narrow, coherent beam.

Preliminary experiments with prototype phase-locked arrays have shown that the output beam narrows as the array size increases from a single element to two by two, three by three, and so forth up to 20 by 20 elements. In all cases, though, the observed beam width is about double what it would be if limited by diffraction, indicating that the phase-locking is not yet perfect. Prototype arrays have emitted just over 1 W output power in pulsed operation, or an order of magnitude less than the peak output of one-dimensional edge-emitting arrays. The figure should improve as the mirror-resistance problem is solved.

To shape and control the output beam, the arrays can be integrated with diffractive or binary optics—lenses of semiconductor or dielectric materials that change abruptly in shape, as opposed to the smooth curve of the usual lens. It may even be possible to modulate the optics electronically, to adjust the relative phase of the lasers so that the beam could be steered at very high speed.

Further issues will also need to be addressed as these lasers move toward commercialization. For example, the reliability of surface-emitting lasers is not yet well quantified, but early reports are encouraging.

CHEMISTRY OF COLOR. The InGaAs/AlGaAs-based heterostructure system, on which most surface-emitters have so far been based, is limited to wavelengths in the near infrared, from 750 to 1100 nm. Much recent attention has focused on extending their materials and wavelength ranges.

Visible wavelengths, including red, orange, yellow and green, are required or desirable in such applications as display systems, laser printing, scanning systems (such as bar-code scanners), short-haul optical communications systems, and optical memory. One recent breakthrough used AlGaInP for visible-wavelength surface-emitters having continuous-wave operation at room temperature, as shown by a group led by one of the authors (Schneider) at Sandia. The devices are rapidly reaching a commercial level of performance, with threshold currents on the order of 1 mA and power outputs exceeding 2 mW continuous wave at the red wavelength of 670 nm.

The longer infrared wavelengths, particularly 1300–1550 nm, feature in communication systems based on optical fiber (such as long-haul phone and data transmission lines). Here, InGaAsP-based surface-emitters operating at 1300 nm have been demonstrated by Iga's group in Tokyo and by John Bowers and his group at the University of California at Santa Barbara in collaboration with Hewlett-Packard Laboratories in Palo Alto, Calif.

For the mirrors in its surface-emitters, Iga's group employed pairs of dielectric coatings such as silicon plus either silicon dioxide or magnesium oxide. Because the pairs differ greatly in refractive index, the mirrors are highly reflective. The layers can also be deposited in a relatively simple process. But as the mirrors conduct no electricity, charge carriers must be injected laterally around and under both mirrors—a requirement that complicates device fabrication. Also, because the dielectric mirrors conduct heat poorly, the density of the current in the small gain region may heat up the devices and perhaps limit their peak output power. That said, all indications are that further refinement of this structure should yield truly practical and efficient 1.3-μm surface-emitter sources.

Overall, prospects for the development of these technologies are bright, despite their immaturity. In the long run, newer materials may be used to broaden their wavelength ranges still further. For example, the materials best at emitting in the green, blue-green, blue and ultraviolet wavelength ranges are the II-VI alloys and the III-V nitrides. These wide-bandgap semiconductors represent the future for laser diodes issuing the shorter wavelengths of the visible spectrum, but they are currently at a much earlier stage of development than the phosphides. At the other end of the spectrum, laser diodes based on the alloys of gallium indium arsenide antimonide and emitting at the wavelengths of 2–5 μm have stirred intense interest; but to date there have been no attempts at using GaInAsSb for vertical-cavity lasers.

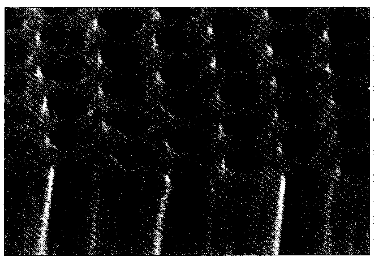
LIKELY USES. Closer at hand, the most promising application is multichannel optical-fiber communications. The technology is being used over short distances to link systems in local-area networks, and is also being pushed to replace electronic buses or backplanes. Present surface-emitter performance and attributes are well matched to multichannel systems of this kind. They can be easily fabricated into multi-emitter arrays, have the power and modal properties to propagate over a few hundred meters, and can be modulated at rates of up to a gigabit per second, while their circular beams are easily coupled into fibers.

For starters, the more mature AlGaAs surface-emitters operating at wavelengths near 850 nm will be used with GaAs or silicon detector technology. That is the plan in the project being pursued by a protégé of the Advanced Research Projects Agency (ARPA) called the Optoelectronics Technology Consortium (OETC); the members include AT&T, General Electric, IBM, and Honeywell. OETC is working toward a 32-channel, 500-Mb/s-per-channel optical data link for board-to-board communications. The transmitter module, which is being developed by AT&T Corp., couples a 32-element AlGaAs surface-emitter array to 32 optical fibers.

Subsequently, as surface-emitters appear with 1.3- and 1.55-μm wavelengths, they may replace the distributed-feedback edge-emitting lasers used today in long-haul optical-fiber communication systems. In these systems, the laser sources must emit light in a single mode within a narrow frequency range in order to minimize dispersion and noise. Now the ultrashort cavity of surface-emitters makes them lase in a single longitudinal mode unless the lasers are too big or driven too hard, whereupon they emit multiple transverse modes. Thus, improving the single-mode performance of surface-emitters is under intense research.

At visible wavelengths, the red surface-emitter is an excellent candidate for short-haul fiber communications. The 650-nm InAlGaP laser is well matched to the attenuation minimum of the rugged plastic fibers.

The same device looks good for printing and scanning because its circular, single-mode, low-divergence beam simplifies the design of the optics needed to focus it on paper or film. Print bars based on light-emitting diodes may well be usurped by laser arrays, whose greater brightness should add to printer speed. And a large flat array of lasers that can be turned on and off like pixels in a computer screen is distinctly faster than a scanning system that relies on rotating mirrors to scan a single beam in two dimensions.



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In this scanning electron micrograph, a photonic lattice structure features holes that are 250 nm in diameter etched into an AlGaAs multilayer wafer. Such photonic lattices, which are fabricated with electron beam lithography and reactive ion beam etching, are currently being investigated for possible use in future generations of low-threshold vertical-cavity lasers.

Visible wavelengths help images, whose contrast often suffers in infrared light. So visible-wavelength surface-emitters could unseat the helium-neon lasers used in supermarket bar code scanners.

Two-dimensional arrays are obviously well suited to image processing and optical computing, especially if individual control electronics turn each laser into a "smart pixel." If detectors are then added to the pixels, the array can both receive multiple optical inputs and process them into optical outputs. Arrays of this type are being developed for photonic switching systems that would interpret and route optical signals, as well as for processors in optical computing systems.

Finally, even electronic computing and information systems could benefit from surface-emitter–based improvements in memory systems. Optical discs have diode laser light focused to a spot on their surface. Here again, the fine beam and integrated micro-optics of surface-emitters should yield low-cost miniature laser systems.

To look farther into the future, holographic memory systems may be read and written by an array of lasers, each accessing a different piece of information stored in the hologram. These and other futuristic applications will continue to steer surface-emitter technology to the marketplace.

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TO PROBE FURTHER. "Vertical Cavity Surface-emitting Lasers," by Kenichi Iga, Fumio Koyama, and Susumu Kinoshita, appeared in the September 1988 *Journal of Quantum Electronics*, vol. 24, pp. 1845–55. It reviews the early work on surface-emitting laser diodes done by Iga and his co-workers in Japan. The June 1991 issue of the same publication reviewed semiconductor lasers with a special section on the vertical-cavity type.

In "Quantum-tailored solid-state devices" [*IEEE Spectrum*, June 1988, pp. 33–37], Timothy J. Drummond, Paul L. Gourley, and Thomas E. Zipperian discuss band gap engineering with strained layers and all-epitaxy mirrors and make mention of vertical-cavity surface-emitting lasers.

"Microlasers" (*Scientific American*, November 1991, pp. 86–94), by Jack L. Jewell, James P. Harbison, and Axel Scherer, goes into epitaxy and the surface processing of vertical-cavity wafers for microlasers.

Finally, "Optical Processes in Microcavities," by Yoshihisa Yamamoto and Richart E. Slusher, which appeared in the June 1993 issue of *Physics Today*, pp. 66–73, reviews upcoming generations of microresonators for quantum electrodynamics and microlasers. ◆

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Kevin L. Lear (M) is a senior member of the technical staff in the Photonics Research Department. He is at present investigating surface-emitting lasers and mirror transport issues. His other interests include quantum-effect devices and compound semiconductor electronics.

Richard P. Schneider Jr. is a senior member of the technical staff in Sandia's Semiconductor Materials Research Department. His research is directed at the epitaxial design and growth of vertical-cavity surface-emitting lasers, including pioneering work on some operating in the red region of the visible spectrum.