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Photon Power

The second photonic revolution is at hand. Coherent is going to lead it.

Got a laser? You're a telecom company. Or so Wall Street seems to have concluded in the last couple of years, in the case of Coherent Inc. (COHR). Like Cree (CREE) (*May 2001 DPR*), Coherent followed the Y2K Pike's Peak of telecom stocks: up four-fold, and back down again. Amusing. Laser light does indeed carry bits. But Coherent's lasers are aimed mainly at atoms.

In terms of coherence, and thus power density, and thus overall energetic order, the laser is millions of times better than Edison's bulb. Photon power ordinarily comes as an incoherent jumble of different frequencies and phase angles; a laser emits in a narrow frequency band, with the waves in phase. By increasing the order, it punches more power through less space—power densities of 20 MW/cm^2 are now routine. Only in a high-voltage power line do power densities routinely run any higher (100 MW per cm^2). In everyday applications, laser light is the pinnacle of highly ordered power.

That much has been true since the laser was invented in 1960. Only recently, however, have high-power lasers followed switches into the quantum recesses of semiconductors. Costs are now falling sharply, and devices are shrinking fast, even as their power levels continue to rise. The new laser is to the old what the transistor was to the vacuum tube. It performs the same function better, cheaper, and in much less space—so much so that, for all practical purposes, it is an altogether new device.

We emphasize the divide between high power and low. Low-power lasers can handle most bit-moving *think* and *see* applications just fine. Indeed, too much power easily becomes a problem when the objective is to send a beam through the very narrow core of a strand of glass, or down to the micron-sized pits on a compact disk. But our economy moves atoms, too, and atoms are a lot heavier than bits. And if it's powerful enough, highly ordered light lets us *move* atoms—stuff—a million times better than the old tools of the thermal and mechanical world. It permits ultra-fine heating, soldering, drilling, cutting, and materials processing, with fantastic improvements in speed, precision, and efficiency. Nothing can move atoms more finely than photons can.

Highly ordered light has already transformed the *think/see* telecommunications legacy of Alexander Graham Bell. The industrial legacies of Thomas Edison, George Westinghouse, and Henry Ford come next. The *move* laser is destined to become as ubiquitous in the atom-moving economy as its low-power counterpart already is in CD players and desktop printers. The second photonic revolution is at hand. Coherent is going to lead it.

Gas Lamps, R.I.P.

If they had a bonfire, the Neanderthals had their lighting technicians. Thomas Edison advanced the technology in 1879, when he managed to sustain an incandescent fire with electrons. Eighty years later, the first ruby-crystal laser transformed low-grade light—supplied by flash lamps—into a single-frequency, coherent beam.

Yet until recently, all our lights, lasers included, could fairly be dismissed as "gas lamps." All depended on the chaotic excitation of a gas (or, at best, a metal filament) in a bottle. All were dreadfully wasteful. For all their blinding brilliance, lasers were the worst—they depended on Edison's inefficient technology to pump photons into a second, equally inefficient, lasing cavity. "Plug-to-beam" efficiencies ran about 1 percent or so, at best, and often dropped below 0.1 percent. It was as if your Pentium depended on the 18,000 vacuum tubes of an Eniac to pump in the bits.

The demise of the gas lamp began in 1948. The first victims were the two- and three-filament bulbs that succeeded Edison's in 1904—vacuum-tube diodes and triodes. Semiconductors, it turned out, could switch and amplify better than bulbs could. As we discussed last month, semiconductor technologies marked the beginning of true quantum engineering—the engineering of ultra-pure materials into atomic-scale junctions (*May 2001 DPR*). In certain semiconductors, the quantum changes in electron states at those junctions emit photons. If the geometry is right, the photons emerge from the surface (or side) of the junction, forming a light-emitting diode (LED). Additional "cladding" layers of different semiconductors, along with wafer-scale mirrors and lenses, can trap charge carriers, guide the waves, and transform the LED into a laser diode.

The first solid-state substitute for a bulb came into being in 1962, when a General Electric (GE) researcher named Nick Holonyak built a light emitter out of gallium arsenide, one of the exotic III-V semiconductors. The LED was much more compact and efficient than the Edison's evacuated globe—it used far fewer electrons to produce better-ordered photons. That was quite an advance. But so far as ordered output went, it still wasn't a laser.

The "gas-lamp" laser is the last of the venerable line, the best, the brightest—and in key respects, the most ridiculous—descendant of Edison's genius. The first aluminum-doped ruby crystal laser was (as the standard histories insist) "solid state" at its center, but it required gas lamps to pump it. The gas lasers that followed just combined flash-lamp and laser in a single gas-filled cavity. To lump these technologies in with the gas lamps of Victorian England is a bit harsh, but still, they reeked of the old world, and barely hinted at the new. Electricity poured in. Heat poured out. Only a tiny fraction of a percent of the power emerged as an intense but tiny beam of coherent light.

The better lasers got, the worse they got. Ambitious engineers pursued the mainframes of their business—big ruby and gas lasers that could cut steel or (perhaps) intercept incoming missiles. One early wag proposed to calibrate a laser beam's power by how many stacked razor blades it could punch its way through, with the unit of power being a "Gillette." To drill more blades, you bought more gas lamps. The power density of the laser beam itself got higher, but the power density of the device as a whole got lower, when you counted the arrays of lamps required to pump it. Behind the magical beam, everything was headed in the wrong direction—toward preposterous inefficiency, mountainous cooling systems, and physical sprawl. For most *move* applications, it made more sense just to stick with conventional technologies.

Not quite all, of course. The beam itself was so good that the market for gas-lamp lasers grew steadily, to over $2 billion last year. Coherent grew and prospered with it. About a third of Coherent's current revenues still come from the gas-lamp technology, and Coherent holds a 60 percent stake in Lambda Physik (LPX on the Frankfurt Stock Exchange), a subsidiary that Coherent took public in a very successful European IPO last October. Lambda is the dominant manufacturer of the deep ultra-violet excimer gas lasers used in the high resolution photolithography that keeps packing more logic gates on to less silicon wafer. But though they defined a steadily growing market, nobody was going to confuse gas-lamp lasers with—say—the silicon chips that they helped fabricate. By comparison with most datacom- and telecom-equipment markets, lasers were going nowhere fast.

Except for lasers that had shed the gas lamp completely. In 1963, just a year after Holonyak built the first semiconductor LED, Herbert Kroemer and Zhores Alferov proposed a (Nobel prize-winning) theory for heterostructure semiconductor devices, in which quantum layers of aluminum and gallium compounds would sandwich carriers and photons to produce coherent laser beams. Other laser-diode architectures emerged too, but it took seven years of additional, independent engineering work by Alferov and Bell Labs to build the first heterostructure device that would become the forerunner of all of today's solid-state lasers.

The early laser diodes attracted little notice. They were very powerful for their size, but they were also tiny. As all quantum technologies do, laser diodes began as very low-power devices, because atomic-scale junctions are inherently frail. Intel (INTC) managed to push its silicon gates down the power curve well before silicon gates were pushed an equivalent distance up the curve by companies like International Rectifier (IRF), IXYS (SYXI), Fairchild Semiconductor (FCS), and Advanced Power (APTI). For its first two decades or so, the laser diode likewise gravitated toward the low-power, bit-centered applications.

The most demanding *think/see* applications didn't need raw power; they needed instead the highest beam intensity (power density) and beam coherence, and the narrowest frequency band. Power requirements actually dropped as photon detectors grew more sensitive, as fiber-optic glass grew more transparent, and as smaller pits got packed more densely on to compact disks. In datacom/telecom applications, higher power is the last and worst alternative; lower power is an objective in itself, because power gets dissipated as heat, and heat is the archenemy of digital order. So laser-diode manufacturers coasted down the power curve, and their sales

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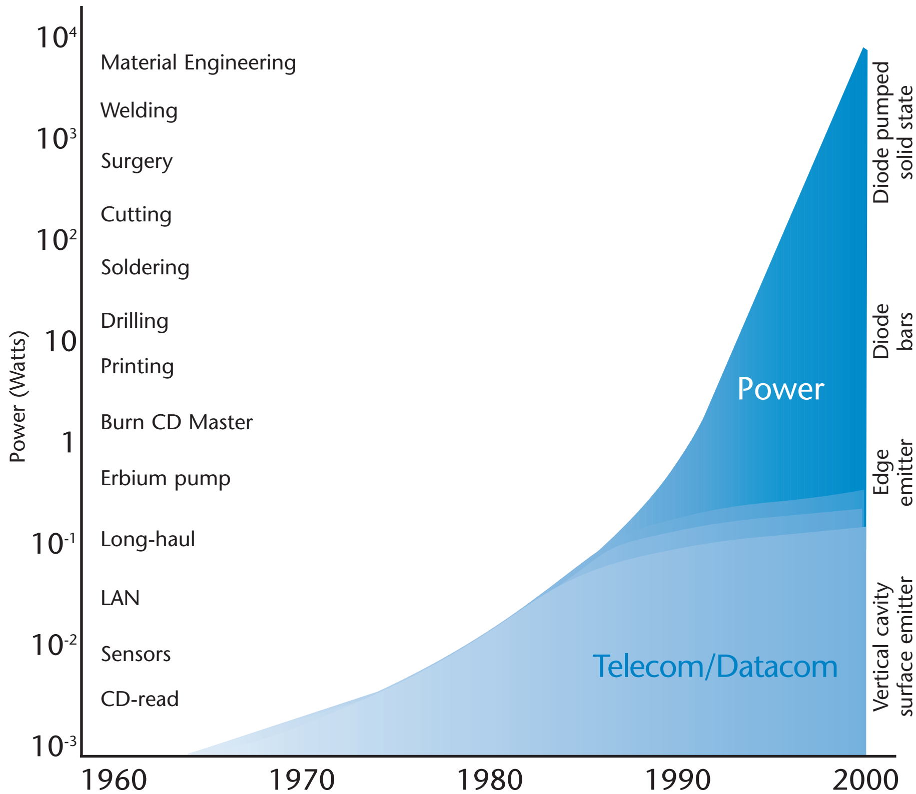
grew stupendously. Laser diodes in datacom equipment are now as cheap and ubiquitous as low-power microprocessors.

The atom-moving world, by contrast, values raw power at least as much as power density, coherence, and narrow frequency band. The heavier the payload you want to move, the more power it takes. Heat is often just what you need to temper or change the granular structures of solids. A milliwatt laser can read a CD, but it takes a thousand times as much power to burn the CD master, and a whole lot more than that to weld the steel body of a car, or drill a hole through a diamond. In *think* applications, the main substitute for a brighter laser is more transparent glass. In *move* applications, progress is measured in opaque Gillettes.

So the laser market split sharply in two. Low-power laser diodes chased bits. Power levels started low, and got lower. Devices started small, and got smaller. Prices started low, and fell. Production volumes started low, and soared. The gas-lamp lasers chased razor blades. Power levels rose, but only with the help of sprawling infrastructure behind the curtain. Prices started high, and didn't drop much. Production volumes grew, but comparatively slowly.

Until quite recently, when a small cluster of companies found ways to push the power of the laser diode up. A lot.

Semiconductor Diode Laser Power



The think/see applications don't need raw power; they need instead high beam intensity and beam coherence, and a narrow frequency band. Most telecom/datacom laser diodes are now as cheap and ubiquitous as most microprocessors. The atom-moving world values a laser's qualities, but demands the raw power that has only recently emerged from semiconductors. A milliwatt laser can read a CD, but it takes a thousand times as much power to burn the CD master, and a whole lot more than that to weld steel, drill a hole, solder chips, cauterize tissue, harden, abrade or micro-alter physical surfaces.

High-Power Laser Diodes

In 1985 a "high-power" laser diode delivered 20 milliwatts. Laser diodes broke the 1-watt barrier around about 1995. They're above 10 Watts today. A 10-Watt light bulb will barely warm your hand; a 10-Watt laser is serious power. And you don't have to stop at one.

In 1995 an obscure laser company called Uniphase grasped the fundamental importance of the low-power/high-power schism, and divided up its own company accordingly. Uniphase sold off the high-power side of its business; four years later, it merged the low-power side with JDS FITEL, to create a telecom laser company (JDSU) that has since attracted much notice on Wall Street. The company that bought the other piece of Uniphase's technical brilliance—the high-power piece—was Coherent.

Coherent made its move into diodes at just the right moment. What it acquired from Uniphase was a leading developer of laser diodes, at just the point where these devices were ready to replace flash lamps in the pumping of high-power lasers. Coherent recognized, in addition, that the future of the power laser diode depended even more on the semiconductor itself than on the architecture and fabrication of the device. In a follow-up acquisition in 1996, Coherent bought 80 percent of Tutcore, a small Finnish company. Tutcore had emerged five years earlier from the physics department of Tampere University of Technology (Tampere, Finland), home of some of the world's finest semiconductor expertise. Lots of other companies were already manufacturing laser diodes, but most were chasing low-power technologies. Tutcore was chasing high power.

The paramount challenge, as Tutcore grasped, was to save the semiconductor from the laser. The laser beam heats the surface of the device that's emitting it, which makes the surface less transparent, which causes still more heating, which ends in a runaway meltdown. *Think* lasers must deliver intense but very narrow beams (matched to the 3- or 4-micron core of a glass fiber, for example), so the area at risk is bounded by a relatively large surface, which makes it easier to cool. Exotic Peltier coolers can be mounted in very close to the hot spot. *Move* lasers, by contrast, must deliver raw power, which means fatter beams and larger emitting surfaces—typically 25 to 50 times larger—with proportionately less surface area for cooling. So to push the *move* devices up the power curve, you have no choice but to reduce heat generation in the semiconductor itself.

Defects in the semiconductor crystal are the main cause of light absorption and thus heat generation. Contaminants, oxygen in particular, are a main cause of defects. Aluminum was added to the early devices to tie down the oxygen. But as epitaxy improved, oxygen impurities fell, and power levels rose, things got to the point where the aluminum itself was doing more harm than good. Coherent chose Tutcore because its half-dozen key scientists were the only team in serious pursuit of an Al-free Indium Gallium Arsenide Phosphide (InGaAsP) laser diode. All others remained locked into Aluminum Gallium Arsenide (AlGaAs).

InGaAsP has an electrons-to-light quantum efficiency of 55 percent, compared to 45 percent for AlGaAs. It is also a significantly better conductor of heat. It's a harder alloy, and its strength inhibits the spread of the most serious "dark-line" defects. InGaAsP lasers also exhibit greater wavelength stability in the face of rising temperatures. This is especially important when multiple laser diodes are combined to deliver higher power from a single laser bar (see below). And when they do fail, InGaAsP lasers fail much more gracefully. Coherent has over 30,000 hours on devices exhibiting less than 5 percent efficiency decline—at least twice as good as AlGaAs alternatives.

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So why isn't everyone doing InGaAsP? Because few manufacturers have mastered the materials science, junction physics, and packaging. Rofin-Sinar (RSTI, spun out of Siemens in 1996) and Boston Laser (Polaroid's laser group spin-out in January 2000) have opted to produce respectably powerful devices by working to keep the oxygen contaminant out of their aluminum semiconductors. Spectra-Physics (owned by Thermo Electron), Mitsui Chemical, OSRAM Opto Semiconductors (a Siemens Osram JV), and Thomson-CSF, all still use aluminum-based compounds. So do a growing number of smaller entrants into the field. Given where the high-power markets are headed, many of these companies are likely to prosper in serving it. Coherent, however, caught the solid-state wave at just the right time, and moved aggressively into the best, if most demanding, Al-free technology.

It's relatively straightforward to grow AlGaAs using the mature metal-organic chemical vapor deposition (MOCVD) process. But MOCVD isn't precise enough for growing InGaAsP devices of the required purity and uniformity. Tutcore made the early decision to employ the more challenging, but far more precise, Molecular Beam Epitaxy (MBE) to grow the critical gallium-based epitaxial layers. It was a bold move, because MBE was still in its commercial infancy. In the years since, Tutcore has accumulated the unique skills needed to build atomic-scale lattice structures, with near-perfect thickness, doping and composition profiles, across a wafer, from wafer to wafer, and from run to run.

MBE remains, to this day, a much more difficult process than MOCVD. The equipment costs substantially more, and MBE grows epitaxy layers more slowly. But you get a much more durable, higher-power laser diode for the trouble. And as for the cost, suffice it to say that the semiconductor industry has a spectacular record of turning expensive into cheap over time, as fabs scale up and production volumes rise. Tutcore now has 70 top scientists, engineers and technicians today, working with half-dozen state-of-the-art MBE machines in a 30,000 square-foot shop. With more to come.

Laser diodes come in two basic architectures. Telecom lasers have to produce low-divergence, single mode beams that can travel long distances in optical fibers. Here, the best architecture is the small-cavity (4- to 5-micron), vertical-cavity, surface emitting laser (VCSEL)—it's easier (and cheaper) to manufacture, the small cavity produces a single-mode beam, and it's the right size to couple directly to a fiber. But it's less efficient, because the light must travel through the body of the diode to get to the surface. Larger cavities, by contrast, produce more power, but less well focused light, and at multi-mode frequencies. *Move* applications need the power, often prefer a somewhat less tightly focused beam, and often find multimode emissions quite acceptable, because source and target are in close proximity. Coherent builds primarily Fabry-Perot laser diodes—broad-stripe, edge-emitting devices with output apertures about 200 microns or more.

The main challenge with the edge-emitting architecture is that charge carriers tend to leak out of the long cavity, and Al-free semiconductors are somewhat worse in this regard. Coherent has solved the problem by retaining an AlGaAs cladding layer on each side of the active junction, just not in the lasing layer itself. There are endless possibilities for further improvement. Jean Michele Pelaprat, president of Coherent's semiconductor group, recognizes that the perfect diode laser for *move* applications would be single-mode and high-power, too. Nothing in the basic physics says that can't be done; getting there is a matter of perfecting architectures and materials. Coherent and others are working on various designs that have V- or Y-shaped active layers, or flared or tapered junctions, that combine narrow (and therefore single-mode) cavities with beam spreading at the diode facet. For now, however, the edge emitters offer the raw power that *move* applications require most.

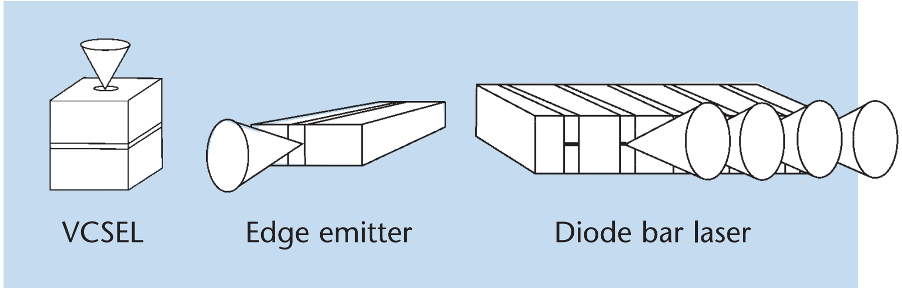
Lasers on a Bar

In the pursuit of semiconductor power, the next step is to pack a lot of identical devices on the same substrate, drive them in parallel, and combine their outputs. Much as other members of our Power Panel do with power transistors. High power IGBT powerchips consist of hundreds of FET switches on a single silicon die, *(April 2000 DPR)*; so do the RF powerchips used in wireless base-station transmitters *(November 2000 DPR)*. Get the timing right, and parallel processing works even better with power than it does with logic.

A handful of companies build industry-standard "bars," consisting of 30 to 60 diodes on a fantastically flexible sliver of semiconductor that's 1 cm long, 1 mm wide, and a 150-microns thick. The diodes emit their light out the 150-micron edge of the bar. Each diode's output is directed through a lens into a single optical fiber; the fibers then route their outputs into a single spot beam. The flat surface of the bar is bonded to a scaffold that provides mechanical support and draws away the heat.

A lot of heat. The Kleenex-like fragment of semiconductor must dissipate up to 200 Watts of heat continuously—more than a Pentium microprocessor generates only intermittently, and that the Pentium spreads across a surface roughly ten times as large. There are huge thermal stresses. The gallium bar, the glue that bonds it to the scaffold, and the scaffold itself are all different materials, which tend to expand by different amounts, bending the bar into a crooked smile. But the bar has to be kept within 1 micron of perfectly flat, to maintain efficient coupling between the laser diodes and the lenses and fibers. The fabrication of these photon-emitter arrays thus presents engineering challenges comparable to any encountered in the manufacture of logic devices.

The necessary skills have only been developed in the past decade, and have only become commercially viable in the last few years. Coherent has again lead the way. From the get go, Coherent's Al-free efficient diodes convert electricity into more light and less heat, which is certainly the best place to start. Because it's a better thermal conductor, the Al-free substrate also sheds its heat faster to the scaffold. For the scaffold itself, Coherent has developed a proprietary microchannel cooling architecture. The company uses natural convection air cooling for its lower power bars (including bars that operate in pulse rather than continuous mode), electrically-driven Peltier coolers for the mid-power range, and water cooling for the highest power devices.



Laser diodes come in two basic architectures; the vertical-cavity surface emitting laser (VCSEL), the telecom favorite, and the atom-moving edge emitter. Single edge emitters produce 100 times the power of fiber-optimized VCSELs; pack 60 on a bar (the same substrate), combine the output, and the 1 cm semiconductor splinter pumps out 100 steel-penetrating photonic Watts.

The rest of Coherent's art lies in highly sensitive choices of materials, and equally delicate techniques for cleaning and preparing surfaces, bonding one component to the next, and packaging the whole. The electrical bonds to the diodes are a special challenge, for example—they're small, they have to be created without damaging the crystal—and they have to deliver up to 5 Amps, at 1.8 V, to each diode, up to 100 Amps for the bar as a whole.

Here, as elsewhere in the world of quantum engineering, the methods are everything, and the proof of a company's skills is found in the products it actually sells. Coherent keeps temperature excursions down to about 0.35°C per Watt of output; the industry norm runs closer to 0.5°C per W. Coherent is thus able to cram 60 laser diodes on a bar, with a diode-to-diode separation of just 15 microns, for a 90 percent fill factor; most of the industry runs about 50 percent. Coherent holds the world record for power from a single bar, with the 100 W beam it achieved last year; the best AlGaAs-based competition achieves under 60 W. And Coherent keeps pushing its own envelope. Eighteen months ago, its best commercial bar delivered 60 W of continuous power.

The frequency stability of Al-free diodes gives Coherent an additional edge on cost. To get useful "parallel processing" out of multiple diodes on a single bar, the diodes must all emit light of very nearly identical frequency. The Al-free designs have uniquely good temperature/frequency stability. Near perfect clones can be manufactured in large numbers across a single wafer, which can then be cut into many usable bars. High uniformity in the performance of individual diodes thus dramatically improves yields per wafer, and cuts costs commensurately.

Bars can be stacked, in turn, to produce further gains in the total power of their combined output. Package a few dozen together, and you get kilowatts of coherent light. Heat is once again the main challenge; Coherent has patented a staircase-like architecture that makes possible more power in a smaller package. Coherent's stack modules lead the industry in power density; the modules themselves represent a wide variety of packages matched to an equally wide variety of end-user applications.

Lasers Pumping Lasers

To push lasers still further up the power curve without surrendering to gas-lamp sprawl, Coherent turns next to the diode-pumped solid-state (DPSS) laser. Coherent's diodes are 55 percent efficient in converting electrons into photons. The second-stage photon-to-photon conversion efficiencies in the pumped laser can run 30 to 50 percent, because all the photons from the pumping laser can be focused precisely on to the target, and tuned precisely to the target's lasing frequency. The overall plug-to-beam efficiency jumps immediately from 1 percent or lower for current gas-lamp devices, to 18 percent on up for DPSS.

Multiple laser-diode bars arrayed to pump a single neodymium:yttrium, aluminum; garnet (Nd:YAG) rod can readily push device power into kilowatt ranges and beyond. Pulse power can be pushed into the terawatt range. And the second-stage laser effectively filters and refines the output of the first-stage pumps, much as a "silicon power plant" assembles multiple sources of lower-grade electric power into a single higher-grade output (*June 2000 DPR*). Beam divergence and modest variations in the frequency of the beams emitted from the diode pumps don't seriously reduce overall pumping efficiency.

Coherent's blue laser consumes 100 W of plug power and is the size of a couple of decks of cards—and can replace a 1.5 kW-gobbling argon gas laser that's ten times the size. Expect a matchbox next.

The second-stage laser can be used, as well, to double the frequency of the output beam. Coherent has developed and expects soon to commercialize a 193 nm deep-ultra-violet solid-state laser—an industry record on the frequency scale. The device uses an edge-emitting laser to pump a proprietary crystal, which in turn pumps a barium borate crystal that provides additional frequency multiplication. The next step is to push up the power levels of high-frequency devices. Ten years ago, green diodes offered the highest frequencies available from semiconductor-based devices, with peak powers of about 10 milliwatts; 10 watt devices are common today. We expect Coherent to push its deep-ultra-violet devices up the same power curve, into the space currently served by Lambda Physik's excimer gas lasers.

Does it make sense for Coherent to encroach on a company in which it still owns a 60 percent interest? Of course it does, replies Bernard Couillaud, Coherent's CEO, with Gallic panache. The alternative is to leave the way open for some other competitor to do so. Semiconductors are almost infinitely plastic and adaptable. And markets open up as soon as the semiconductors deliver. Chip manufacturers like Intel use excimer lasers because shorter wave lengths etch smaller gates. Soft X-rays can peer through the opaque silicon layers to check on the condition of a wafer packed with Pentiums. Higher frequency delivers higher power density and higher precision, which invariably lead to new, high-value applications.

With the arrival of diode pumps, the pumped laser is finally solid state from end to end. Every component of the device is now small, and can get a lot smaller. And every advance in one component of the solid-state laser propels complementary advances in others. The more efficient the semiconductor, the smaller the cooling system, for example. The largest remaining components of the solid-state lasers are the (solid) "cavities" at which the pumps are aimed, and they too are now collapsing inward. A typical micro-rod in a 100 mW green laser is 1.2 mm long x 0.2 mm in diameter, and most of that volume is there for manufacturing, handling, mounting, and thermal considerations, not for the lasing itself. Higher power applications use larger rods (300 x 30 mm), to make room for a larger array of diode pumps around the crystal. But as the individual pumps grow more powerful, the rods themselves can continue to shrink.

The high-power laser is now set to evolve in the same direction as the high-power computer—shrinking inexorably in size, and marching relentlessly toward low-cost mass production. The old mainframes of the laser industry, with giant power supplies and even larger cooling systems, can now collapse into devices the size of PCs, or Palms, or smaller still—with power and power density continuing to rise even as the systems themselves continue to shrink. Coherent's blue laser consumes 100 W of plug power and is the size of a couple of decks of cards—and can replace a 1.5 kW-gobbling argon gas laser that's ten times the size. Expect a matchbox next.

And then something much smaller than that. Coherent recently developed and patented the world's first optically pumped semiconductor (OPS) laser—a device in which the Nd:YAG crystal is replaced with a semiconductor VCSEL. Get the geometry and materials just right, and it turns out that a VCSEL can be powered with photons rather than electrons. With a co-packaged edge-emitting diode serving as the pump, a VCSEL's clean output can be boosted fifty fold or more. Beyond the OPS lies the Quantum Cascade Laser (QCL), with the potential to push laser diode power up a thousand-fold or more. Invented by a Bell Labs physicist in 1994, the QCL takes the photon-pumping-photon to its logical limit, by assembling multiple quantum-well junctions within a single semiconductor device. No company is close to owning that exotic space yet. But Coherent has an established track record of building or buying its way into such breakthroughs, when the time is ripe.

Highly Ordered Power

Order is the most valuable (if least understood) good sold in our energy economy. As we have written before, there is no energy crisis, no scarcity of energy. Energy is abundant, and is never "consumed" in any event—all energy is always "conserved," the first law of thermodynamics declares that it must be. The one and only scarcity, as enduring as time itself, is the scarcity of order, and the excess of entropy, its antithesis.

The order is worth much more than the energy itself. Wired businesses pay a ten-fold premium for high-9s electrons, through the cost of expensive but rarely used equipment to back up the low-9s grid. A kilowatt-hour of grid electricity costs 50 times as much as its thermal equivalent in coal—the difference is all in the order. A kilowatt-hour of laser light costs thousands of times more than its equivalent in lumens from an ordinary bulb.

Higher-grade power commands these premiums because it can do things that more chaotic forms of power can't begin to match. Nowhere more so than with light. Lasers already move the ink in desktop printers; they are now rapidly taking over the ink-moving responsibilities in every other kind of printing. They paint sub-micron images on chip masks, etch silicon and metal, and solder opto-electronic chips without destroying the silicon real estate around them. They are sharp and fine enough to remove hair, or reshape the surface of the eye, or cauterize tissue through an endoscope, without damage to surrounding tissues. They can be tuned precisely enough to dump power into a photo-reactive dye that accumulates in cancerous tissues, without killing healthy cells nearby. They can be tuned finely enough to detect individual pollutants in an exhaust gas, or measure fluid flow speeds, or enable unique forms of microscopy. And as they push up the power curve, they supply unequaled precision in the bulk processing of work-a-day materials—heat treating, welding, polymer bonding, sintering, soldering, epoxy curing, and in the hardening, abrading, and milling of surfaces.

The potential applications have been there all along; it's the laser technology itself that has recently raced forward to meet them. From here on out it's a matter of engineering, fabrication, packaging—the real-world, detail-sweating improvements on existing know-how that double performance, and then double it again, in the magic kingdom of quantum technology. Solid-state lasers are now going the way of all solid-state quantum technologies. They are getting smaller, cooler, and more efficient. Their production is being automated. Huge economies of scale are kicking in, and costs are plummeting, even as performance rises.

At this point in the technology's evolution, the pay-off for pushing the solid-state laser up the power curve is even larger than the pay-off for pushing it down. Though the bit-moving and photon-moving devices of *think/see* industries have multiplied very fast, the atom-moving legacy industries still consume far more power. Low-power telecom/datacom devices currently account for about three-quarters of the $6.6B market for diode lasers, and revenues from this sector are doubling year to year. But the low-power market is all but commoditized now, and very familiar to investors. The high-power market is neither—and the $1.5B market for non-telecom laser diodes grew 50 percent last year, and is picking up speed. Diode lasers are now rapidly invading the non-diode laser market, which represents an additional $2.2B in revenues (about two-thirds of the applications are in manufacturing and material processing, the rest mainly medical). And most of the market for high-power lasers lies in applications where lasers aren't yet used at all.

In *move* applications, the better ordered the power, the better we can aim it, and the less extraneous junk we end up having to move along with the real target. Microwaves can heat just the water in the soup, not all the air and stovetop around it; lasers can perform the almost impossibly delicate task of separating one isotope from another. Power electronics that boost frequency or condition voltage and current can shrink electric motors and transformers ten-fold, or a hundred-fold. Highly ordered power is simply more "intelligent" than the alternative, here, in that it can be precisely aimed, tuned, and matched to the payload.

Two-thirds of Coherent's sales now come from diode and DPSS lasers. Telecom/datacom companies are customers too, but account for well under 10 percent of the company's $480 million in global revenues. Last September, Coherent consolidated all its high-power operations (optics, laser and semiconductors) in its new Coherent Photonics Group, and its telecom/datacom operations in a separate Telecom-Actives Group. Coherent's Finnish operation provides wafers for both divisions. But Coherent as a whole is squarely positioned on the high-power side of the great laser divide.

Lasers are now making the critical transition from custom-designed component of exotic equipment to general-purpose building block of the mass-production economy. Low-power solid-state lasers have already made that transition, and are now ubiquitous and routine in the moving of bits. With power output rising, and size and cost falling, higher-power lasers are now set to become equally ubiquitous and routine in the moving of atoms. Radar made the transition from high-tech military secret to factory floor and microwave oven. Microprocessors started in supercomputers and ended up in car engines and kitchen appliances. Power lasers are next. Coherent is building them.

Peter Huber and Mark Mills
May 31, 2001

The Power Panel

Ascendant Technology	Company (Symbol)	Reference Date	Reference Price	5/31/01 Price	52wk Range	Market Cap	Customers
Photon Power	Coherent (COHR)	5/31/01	35.50	35.50	25.00 - 93.50	982m	Hitachi, Ford, Visteon, United Technologies, JDS Uniphase, Boeing, Applied Materials, Heidelberg Printing, Seagate
Powerchips	Cree Inc. (CREE)	4/30/01	21.53	28.70	12.21 - 87.50	2.1b	Siemens, Sumitomo, Microsemi, Infineon, OSRAM, Kansai Electric Power
	Microsemi (MSCC)	3/30/01	28.00	57.50	18.94 - 63.29	803m	Lockheed Martin, Mitsubishi, Medtronic, Boeing, Motorola, Palm, Compaq
	Fairchild Semiconductor (FCS)	1/22/01	17.69	19.75	11.19 - 49.00	2.0b	GE, Emerson Electric, Rockwell, Siemens, Bosch, PowerOne, Artesyn, Invensys, IBM, Delta, Marconi
	IXYS (SYXI)	3/31/00	6.78	13.01	9.19 - 45.38	346m	Rockwell, ABB, Emerson, Still GmbH Eurotherm Ltd. (UK), Alpha Technology
	International Rectifier (IRF)	3/31/00	38.13	60.06	27.38 - 69.50	3.8b	Nokia, Lucent, Ericcson, APC, Emerson, Intel, AMD, Ford, Siemens, DaimlerChrysler, Bosch, Bose, Delphi, Ford, TRW
	Advanced Power (APTI)	8/7/00	15.00	12.85	8.44 - 49.63	111m	Alcatel, Ericsson, ITI, Power-One, Advanced Energy Industries, Emerson
	Infineon (IFX)	11/27/00	43.75	34.35	31.44 - 88.25	21.5b	Siemens, Visteon, Bosch, Mansmann-Sachs, Hella, Delphi
Network Transmission and UPS: High-temperature superconductor	ABB (ABB)	9/29/00	24.24**	18.10	16.68 - 18.95**	N/A	National Grid (UK), Microsoft, Commonwealth Edison, American Electric Power
	American Superconductor (AMSC)	9/30/99	15.38	25.95	10.75 - 61.88	526m	ABB, Edison (Italy), ST Microelectronics, Pirelli Cables, Detroit Edison, Electricite de France
Power: Heavy-Iron-Lite	General Electric (GE)	9/29/00	57.81	49.00	36.42 - 60.50	486.7b	Reliant Energy, Enron, Calpine, Trans Alta, Abener Energia, S.A.
	Catalytica Energy Systems (CESI)	9/29/00	12.38	19.25	9.13 - 22.01	248m	GE, Kawasaki Turbines, Enron, Rolls Royce, Solar Turbines
Distributed Power Generation Microturbines	Capstone Turbine Corp. (CPST)	6/29/00	16.00*	32.87	17.75 - 98.50	2.5b	Chevron, Williams ECU, Tokyo Gas, Reliant Energy
Fuel Cells	FuelCell Energy (FCEL)	8/25/00	49.88	73.97	20.00 - 108.75	1.2b	Santa Clara, RWE and Ruhrgas (Germany), General Dynamics, LADWP
Silicon Power Plants In-the-room DC and AC Power Plants	Emerson (EMR)	5/31/00	59.00	67.71	57.25 - 79.75	29.0b	Citicorp, Verizon, Nokia, Motorola, Cisco, Exodus, Qwest, Level 3, Lucent
	Power-One (PWER)	*(see below)*					
Motherboard Power Bricks, High-end DC/DC converters	Power-One (PWER)	4/28/00	22.75	20.44	12.06 - 89.81	1.6b	Cisco, Nortel, Teradyne, Lucent, Ericsson
Electron Storage & Ride-Through Ultracapacitors	Maxwell Technologies (MXWL)	2/23/01	16.72	21.06	12.06 - 22.56	211m	GM, Delphi, Visteon, Valeo, Onemocall, EPCOS, Boeing, Lockheed Martin, Rockwell
Flywheels	Active Power (ACPW)	8/8/00	17.00*	24.45	12.75 - 79.75	967m	Enron, Broadwing, Micron Technologies, PSI Net, Corncast Cable, ABC
	Beacon Power (BCON)	11/16/00	6.00*	6.65	3.65 - 10.75	282m	Century Communications, Verizon, SDG&E, TLER Associates, Cox Cable
Hydrogen Generation	Proton Energy Systems (PRTN)	9/29/00	17.00*	12.48	5.25 - 36.00	413m	Matheson Gas, NASA

Note: This table lists technologies in the Powercosm Paradigm, and representative companies that possess the ascendant technologies. But by no means are the technologies exclusive to these companies. In keeping with our objective of providing a technology strategy report, companies appear on this list only for the core competencies, without any judgment of market price or timing. Reference Price is a company's closing stock price on the Reference Date, the date on which the Power Panel was generated for the Digital Power Report in which the company was added to the Table. All "current" stock prices and new Reference Prices/Dates are based on the closing price for the last trading day prior to publication. IPO reference dates, however, are the day of the IPO. Though the Reference Price/Date is of necessity prior to final editorial, printing and distribution of the Digital Power Report, no notice of company changes is given prior to publication. Huber and Mills may hold positions in companies discussed in this newsletter or listed on the panel, and may provide technology assessment services for firms that have interests in the companies.

** Offering price at the time of IPO.*

*** Effective April 6, 2001, ABB was listed on the NYSE. The reference price has been adjusted to reflect this change. The 52-week range covers the period from April 6, 2001 only, the start date for high-low tracking on the NYSE listing.*