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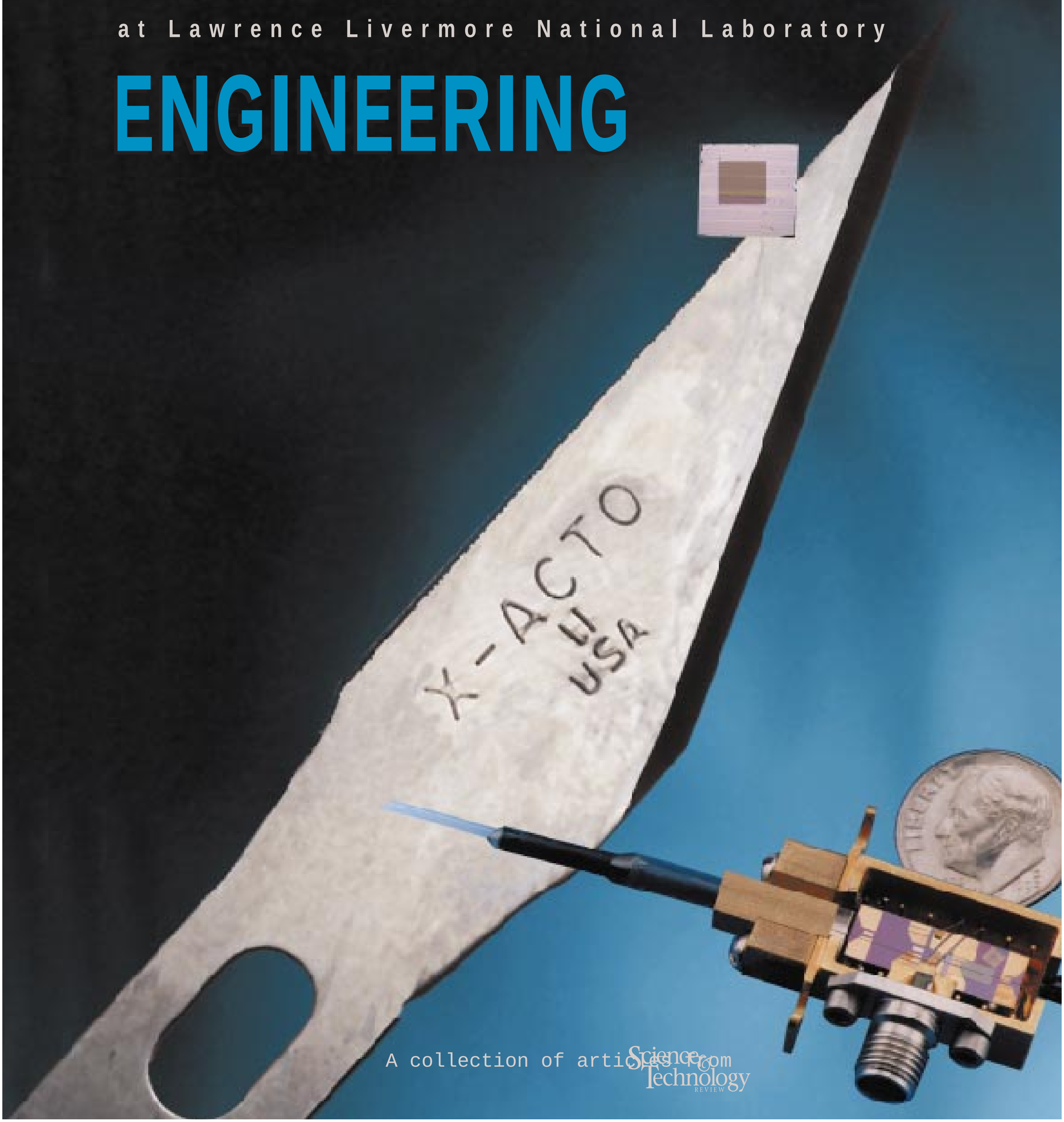
MICROTECHNOLOGY

at Lawrence Livermore National Laboratory

ENGINEERING



A collection of articles from Science & Technology Review

About the Cover

A number of new technologies have been developed by Lawrence Livermore's Microtechnology Center, each one having the distinction of being smaller than any comparable product. One of them, a fullerene waveguide array that will be a part of a photonic radiation sensor system at the Laboratory's National Ignition Facility, is shown next to an X-acto knife blade. Another, a semiconductor optical amplifier that reduces crosstalk and noise in fiber-optic communications, is shown next to a dime. The waveguide array image is about five times actual size; the image of the optical amplifier is about twice actual size.

Cover design: George Kitrinos

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy. At Livermore, we focus science and technology on assuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published ten times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

Please address any correspondence (including name and address changes) to *S&TR*, Mail Stop L-664, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, or telephone (510) 422-8961. Our electronic mail address is *hunter6@llnl.gov*.

Prepared by **LLNL** under contract
No. W-7405-Eng-48

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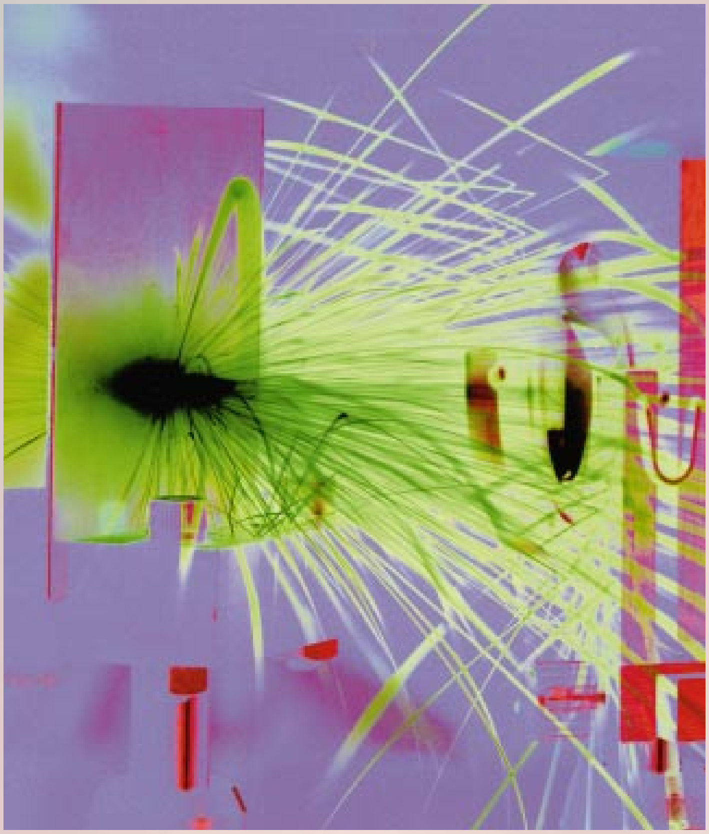
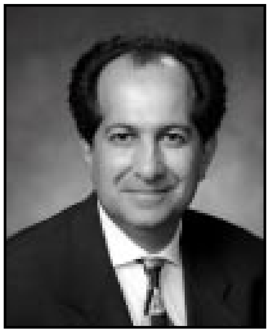


Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

UCRL-ID-129545
Distribution Category UC-700



Introduction to Microtechnology

WHEN scientists announced that they could measure the size of an individual atom, a common response from the lay community was, “That’s impressive, but why would I want to measure an atom?” However, when engineers developed a way to incorporate this technology into a machine that can measure surface irregularities caused by a single atom of a material, it was easier to communicate the significance to the average citizen. This measurement technology, when combined with other microtechnologies, enables production of a computer microchip that will store 1000 times the data of previous chips, or allow us to build dime-sized amplifiers to make fiber-optic communications faster and clearer. It is much easier for the world at large to understand the importance of a new technology when they can see how it benefits them.

We’ve selected the following six articles, previously published in Lawrence Livermore’s *Science & Technology Review*, to convey the contributions made by just one area of the Engineering Directorate. The first article, focusing on our Microtechnology Center, sets the stage for describing our work in this area and features some of the inventions that have been the result of technology developed here. Other articles include “Silicon Microbench Technology,” which tells how our work has enhanced fiber-optic communication; “Speeding the Gene Hunt: High-Speed DNA Sequencing,” which describes genetic research enabled by microtechnology; “Signal Speed Gets Boost from Tiny Optical Amplifier,” which features additional microtechnology contributions to fiber optics; and “High-Repetition-Rate, Diode-Pumped, Solid-State Slab Lasers,” which illustrates the role microtechnology has played in the development of these lasers.

Microtechnology is not an end in itself. It does, however, provide solutions to problems in almost countless areas, enriching human lives everywhere.
—Spiros Dimolitsas

■ Spiros Dimolitsas, Associate Director, Engineering.

The Microtechnology Center

When Smaller Is Better

From thin-film windows to microactuators to photonic devices—the Center contributes to stockpile stewardship, bioscience, and nonproliferation projects at Livermore.

A dime-sized amplifier makes fiber-optic communications faster and clearer. A portable DNA analyzer helps detect and identify organisms in the field, including human remains and biological warfare agents. A tiny gripper inserted in a blood vessel treats aneurysms in the brain to ward off potential strokes. What do these technologies have in common? Each one is smaller than any comparable product, opening up a host of new applications. And each originated in Lawrence Livermore National Laboratory's Microtechnology Center.

In the late 1960s, Livermore scientists and engineers began making miniature devices for high-speed diagnostic equipment required for nuclear tests. For many years, before the development of Silicon Valley and the ready availability of microchips for a broad array of uses, Laboratory engineers fabricated chips to their own specifications for high-speed switches, high-speed integrated circuits, and radiation detectors. By the early 1980s, Livermore was fabricating thin-film membranes for use as x-ray windows in low-energy x-ray experiments, as x-ray filters, as debris shields for the Extreme Ultraviolet Lithography Program, and as targets for high-energy electron experiments in which x rays are generated.

These passive microstructures have been applied to dozens of projects. They have served as diagnostic devices for Livermore's Nova laser experiments and will do the same for experiments at the National Ignition Facility (NIF). Another microstructure, a novel thin-film window developed by Glenn Meyer and Dino Ciarlo, plays a critical role in a new, more efficient electron-beam system for processing inks, adhesives, and coatings. Laboratory scientists, led by Booth Myers and Hao-Lin Chen, teamed with American International Technologies Inc. of Torrance, California, on this project and won an R&D 100 Award in 1995. Conventional electron-beam processing systems are inefficient, delivering about 5% of the beam's energy to the polymer being cured. With this new window, efficiencies greater than 75% were achieved. The team also recently won a 1997 Federal Laboratory Consortium Award for Excellence in Technology Transfer.

In the mid-1980s, Livermore began combining micro-optical devices with microelectronics for extremely high-speed, fiber-optic data transmission. Photonic devices have since found their way into many microtechnologies that incorporate optical fibers for transmission of laser light.

Livermore stopped fabricating silicon-based electronic circuits when commercial microchips became available in almost every configuration imaginable. But invention by no means stopped. Today, the Microtechnology Center, now headed by physical chemist and engineer Ray Mariella, invents and applies microfabricated components, including photonic devices, microstructures, and microinstruments, to directly support Laboratory projects in science-based stockpile stewardship, nonproliferation, and biomedical research. At any given moment, the Center has about 25 projects in the works. The Center's major recent and ongoing projects are highlighted here.

The Center's state-of-the-art fabrication facilities are centered in a building whose location was selected because the area had the smallest vibrations within the Laboratory site, permitting the high-resolution microlithography that the Center performs. Microdevices can be fabricated there in any of three material systems:

- Silicon and silicon compounds for microstructures and microelectromechanical systems applications.
- Gallium-arsenide for photonics applications.
- Lithium niobate for electro-optic applications, such as phase and amplitude modulators.

The Center has the equipment and infrastructure needed for lithography, etching, diffusion, wafer bonding, and thin-film deposition and vacuum techniques. Its dry laboratories are used for surface inspections, packaging, and electrical and optical device testing. Groundbreaking recently took place for an addition that will increase clean-room space by 65%. The backbone of the Center is an interdisciplinary group of about 50 electronics, mechanical, chemical, and biomedical engineers, physicists, and technical support personnel (Figure 1). According to Mariella, "Ideas, technologies, and capabilities are shared at frequent brainstorming sessions, so staff can find solutions to programmatic problems quickly."

Putting Light to Work

Photonics work at Livermore got its start from the need to obtain remote, highly accurate measurements at nuclear weapons tests. Photonic systems—which manipulate and exploit light for control, communication, sensing, and information display—were the ideal solution because signals can travel on them for long distances at the speed of light with very little power loss. After several years of development, Livermore successfully fielded its first photonic system for measurement of ionizing radiation from a nuclear weapon at the Nevada

Figure 1. Most members of the Microtechnology Center staff.

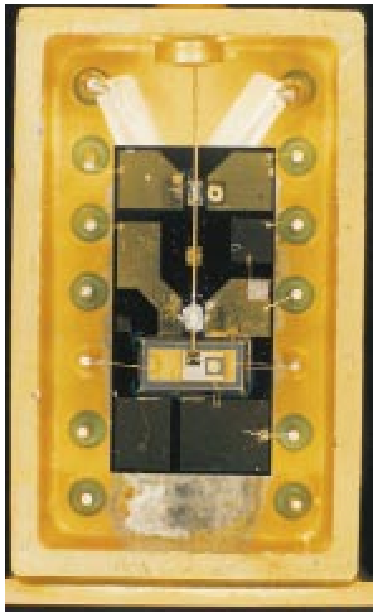


Figure 2. With the silicon microbench, two polysilicon heating elements and gold solder attachment bases provide the means for attaching the optical fiber. While the fiber is held in position, current is passed through the heater to reflow the solder, which wicks around the metalized fiber without disturbing the alignment. This new method avoids thermal shifts and simplifies the alignment process.

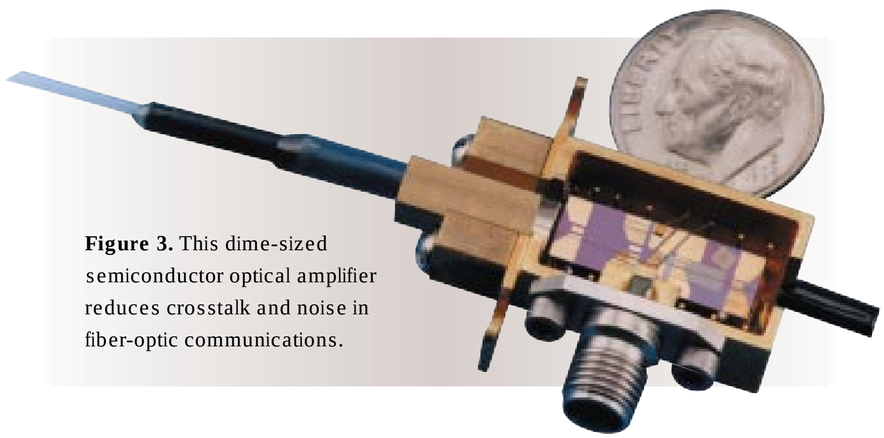


Figure 3. This dime-sized semiconductor optical amplifier reduces crosstalk and noise in fiber-optic communications.

Test Site in 1989. This system made available very high-resolution data that conventional measuring techniques could not deliver. In 1991, Livermore was awarded the DOE Weapons Excellence Award for this work.

A photonic network is typically made up of optical fibers, waveguides, amplifiers, receivers, wavelength selection elements, and modulators, sometimes all on a single chip. One of the Laboratory's contributions to the photonics field has been its novel application of silicon micromachining capabilities, which have been critical to packaging photonic components in a cost-effective manner. In 1994, Mike Pocha, Dan Nelson, and Ted Strand won an R&D 100 Award for the development of a silicon "microbench" that reduces the time needed to align and connect the optical fiber in photonic components. Because of the submicrometer alignment tolerances, the standard manual process was extremely time consuming and therefore expensive. The team's technique (Figure 2) provides just enough heat to melt the microdrops of solder needed to make the connection, allowing a rapid manual alignment and connection of the fiber to a laser diode or a lithium niobate modulator in less than five minutes and reducing the cost for this work by 90%.

Photonic devices are finding their way into two different parts of the Laboratory's science-based stockpile stewardship program. One is ultrascale computing, which soon will be used for simulations of nuclear tests; the other is diagnostics for NIF.

Computing on a large scale requires the cooperative action of thousands of microprocessors sharing tremendous volumes of data. This data sharing demands a communication "fabric" of very high bandwidth and low latency (short time delay) to enable the microprocessors to function without waiting for data. Optical fibers are an ideal medium provided that the optical signals are sufficiently amplified so that there are enough photons to go around for the many receiver nodes. Existing amplifiers had problems: erbium-doped fiber amplifiers are bulky and expensive, and conventional semiconductor optical amplifiers produce too much crosstalk at transmission rates above 1 gigabit per second.

To solve this problem, Sol DiJaili, Frank Patterson, Jeff Walker, Robert Deri, William Goward, and Holly Peterson developed a miniature, low-cost semiconductor optical amplifier (Figure 3). They applied state-of-the-art microfabrication techniques including molecular beam epitaxy to grow device wafers and chemically assisted ion-beam etching to make the device structures. The team won a 1996 R&D 100 Award for their new device, which can be used not only for computer interconnections but also in wide-area networks and for transmitting visual images.

They then replaced the standard gain medium inside the waveguide of the amplifier with a tiny vertical-cavity surface-emitting laser and took advantage of some basic laser properties to reduce crosstalk by a factor of 10,000. The photons' stimulated emission in the gain medium when lasing occurs acts as a clamp on the signal gain, eliminating the fluctuation. Signal channels at multiple optical wavelengths can pass through the waveguide with virtually no crosstalk among these channels. The lasing action also speeds recovery time of signals through the waveguide, from a billionth of a second to about 20 trillionths of a second. Thus, the amplifier can successfully track the amplification of a serial bit stream at very high bit rates.

The Microtechnology Center is also applying photonics technology at NIF. Because NIF's 192 laser beams will be aimed at such small targets (about the size of mustard seeds), NIF will need much faster radiation diagnostics than those used at the Nevada Test Site. Mike Pocha and Howard Lee are developing photonic radiation sensors that will modulate an optical beam in response to an ionizing radiation input and then record it using single-shot optical samplers having a response time of 100 femtoseconds (quadrillionths of a second). Pocha and Lee are investigating the use of waveguides made of nonlinear optical material to perform the extremely high-speed signal gating required to sample at these high data rates. (A nonlinear optical material is one whose index of refraction can be changed by the introduction of another light beam.) These nonlinear gates will be capable of switching sequential slices of the radiation-modulated optical signal into an array of relatively slow-speed optical detectors. A material that may have the right nonlinear properties is fullerene (C_{70}), whose discoverers recently won the Nobel Prize in Chemistry. (Fullerene is a van der Waals crystal with molecules shaped like Buckminster Fuller's geodesic domes, hence its name.) The world's first fullerene waveguide array, which is still undergoing development, is shown in Figure 4. Work continues on this project so that a fully functional system will be on line in time for the testing of NIF, which is scheduled for 2002.

Analyses in Miniature

Analyzing DNA, testing for HIV, and identifying pathogens and poisons used in biological and chemical warfare all require sampling a range of products. Supporting the Laboratory's bioscience research program and its nonproliferation efforts, the Microtechnology Center has developed several cutting-edge microdevices that facilitate biological and chemical sampling and analysis in the field, allowing real-time detection. Because some samples cannot survive transport from the field to a remote laboratory, field analysis is often the only solution.

Biological and chemical sampling with micro-instruments offers other advantages as well. Smaller instruments have lower power requirements. Highly integrated and automated sample handling systems usually result in improved productivity and less sample contamination. Also, because analytical diagnostic procedures sometimes produce hazardous wastes, smaller systems mean less waste. However, extremely small-volume chambers require greater sensitivity in order to identify the extremely small trace samples.

A team led by Ray Mariella has patented a new system that eases alignment and increases the accuracy of flow cytometry. Flow cytometry is a powerful diagnostic tool used to characterize and categorize biological cells and/or their contents, such as DNA. It is used by laboratories throughout the world for blood typing and for testing for a wide variety of diseases and viruses, including HIV. The cells flow in single file in solution while the experimenter directs one or more beams of laser light at them and observes the scattered light, which is caused by variations in the cells or DNA. Instead of using a microscope lens or an externally positioned optical fiber as a detector, Mariella's system uses the flow stream itself as a waveguide for the laser light,

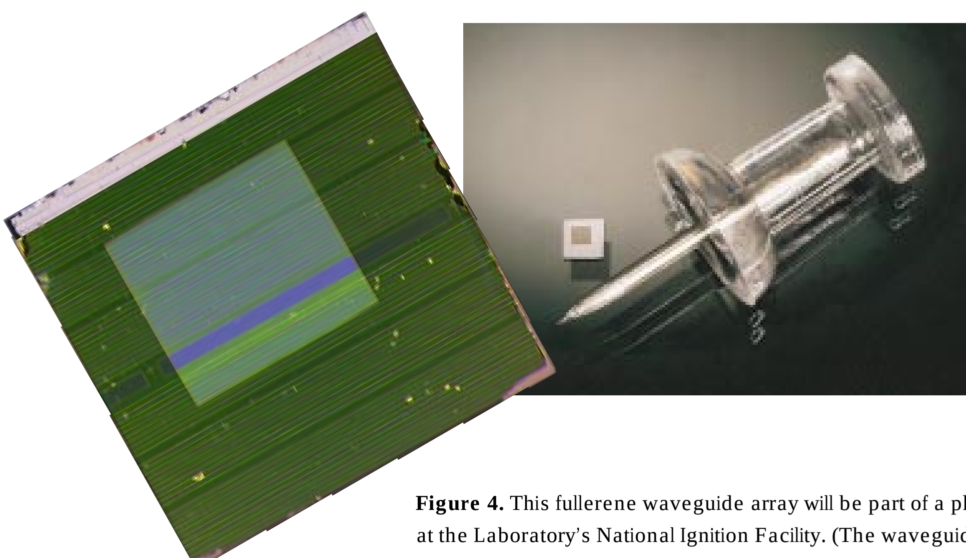
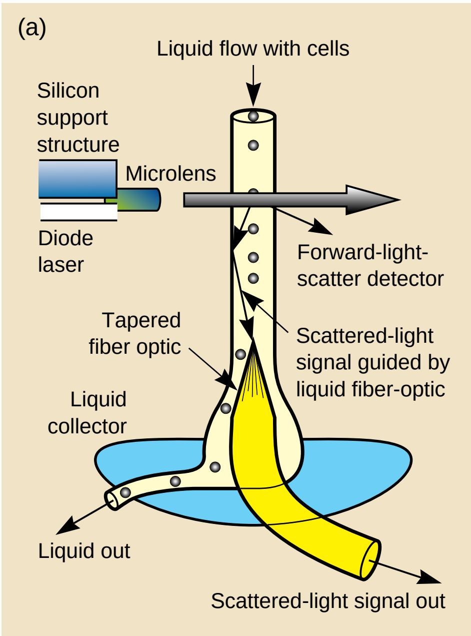


Figure 4. This fullerene waveguide array will be part of a photonic radiation sensor system at the Laboratory's National Ignition Facility. (The waveguide was photographed next to a push pin to indicate scale; the waveguide on p. 3 is between two X-acto knife blades.)



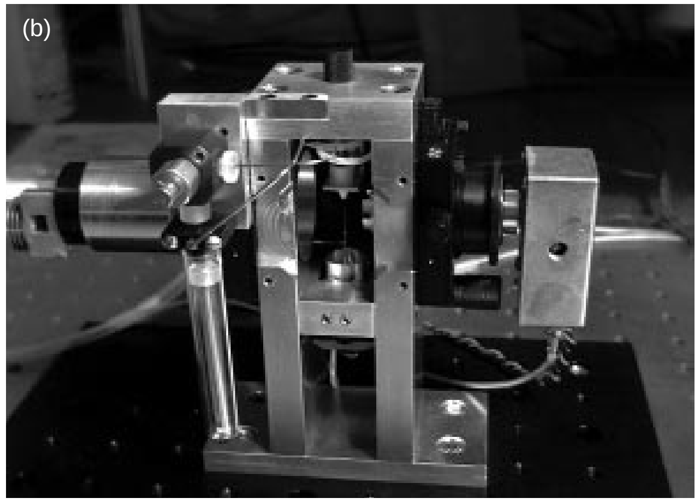


Figure 5. (a) Schematic and (b) demonstration model of the new flow cytometer. As a cell passes through the laser beam on the left, the cell simultaneously scatters (reflects) the laser light into the forward-light-scatter and the right-angle-scatter detectors. The scatter pattern reveals the cell's size and internal structure.

capturing the light and transmitting it to an optical detector. Alignment simply requires lining up the light source onto the flow stream and placing the detector into the same stream (Figure 5). With this system, measurements are up to three times as accurate as those taken with conventional systems.

At international joint field trials last fall at Dugway, Utah, the new flow cytometer performed extremely well detecting simulated biological warfare agents. Participants from the U.S., the U.K., Canada, and France used a variety of instruments to detect four simulants. The Livermore flow cytometer detected 87% of all the unknowns with a false positive rate of just 0.4%.

Dino Ciarlo, Jim Folta, and William Benett developed a miniature sample injector that can be used in Mariella's flow cytometer. Flow channels are formed by etching three silicon wafers and bonding them into a single chip. Fluidic connections are made to this injector chip via a plastic block. A thin gasket, laser-cut from an elastomeric material, forms a seal between the silicon chip and the block. The front edge of the silicon chip remains exposed to allow fluid to freely exit through an edge port into the optical detection system.

A Laboratory team headed by M. Allen Northrup has developed an portable DNA analyzer that is small enough to fit in a briefcase. It is also fast (Figure 6). This unit, the world's only battery-powered DNA analyzer, moves analysis out of the laboratory for the first time. Folta and Benett developed a disposable polypropylene liner for the analyzer's tiny heated chamber where the polymerase chain reaction occurs. The liner facilitates rapid reuse of the chamber and eliminates tedious cleaning and possible contamination. The entire chamber is a tiny chip of silicon. As the reaction progresses, the team uses a fluorescent signal to analyze the DNA to determine whether it matches that of a particular subject.

LLNL has delivered one of these units to the Department of Defense

Figure 6. The Microtechnology Center's DNA analyzer and computer system fit in a briefcase. The polymerase chain reaction chamber and related analysis equipment are on the right side of the case.

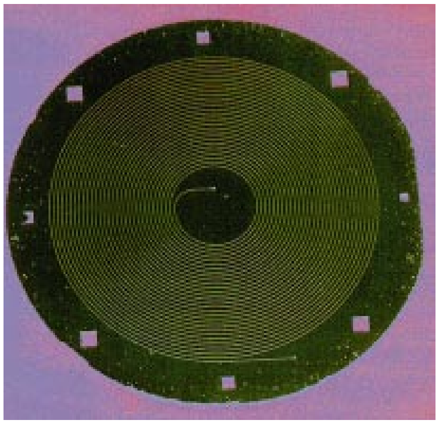


Figure 7. The column for the miniature gas chromatograph has been reduced to two silicon wafers bonded together. Here, one wafer is shown with its coiled groove 100 micrometers wide and several meters long.

Figure 8. The microgripper, the size of two grains of salt, is the first in a series of new surgical microtools being developed by the Laboratory's Center for Healthcare Technologies.

Armed Forces Institute of Pathology, which is using it to quickly identify human remains in the field, test food and water for contamination in remote locations, and identify pathogenic bacteria on the battlefield.

The Microtechnology Center is also supporting the Laboratory's DNA sequencing work for the Human Genome Project. The Center has developed etched and bonded microchannel glass plates to speed up the sequencing process, and a patent is pending on the new bonding process.

Conrad Yu of the Center is participating in work on a miniature, portable, low-power gas chromatograph to support the Laboratory's program in nonproliferation to counter the spread of chemical weapons. Gas chromatography is a proven method for identifying liquid or gas species, with detection sensitivities as high as parts per billion. Conventional gas chromatographs, however, are several cubic feet in size and typically take about 20 minutes to analyze a gas sample. A mini unit works faster, often requiring just one minute to complete an analysis, and would be very useful to carry into an area where chemical weapons or other poisonous gases are suspected to have been used. Someday this unit could also be used at home for sniffing out radon gas.

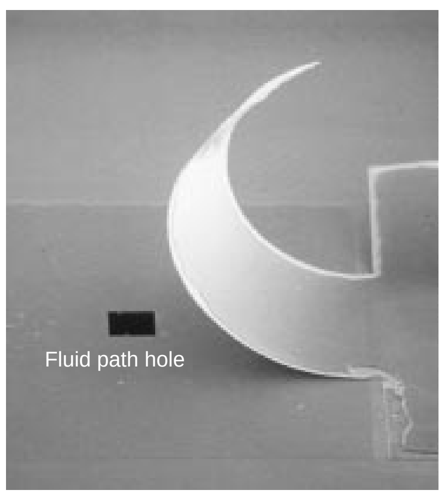


Figure 9. The 200-micrometer-long microvalve is shown in the open position, revealing an etched hole.

Yu has developed a micromachined, silicon sample injector about the size of a little fingernail. He has also reduced the size of the chromatograph's column where the various elements in the sample are separated before being directed to the detector where they are identified. The column has been reduced from 1.6 liters (100 cubic inches) for a laboratory-sized unit to a coil etched on a silicon wafer. A circular column 100 micrometers wide and several meters long is etched on two silicon wafers that are bonded together. The entire instrument occupies about 0.16 liter (10 cubic inches) (Figure 7).

Microtools for Better Health

A new surgical tool for treating aneurysms, the silicon microgripper is about the size of two salt grains—1 by 0.2 by 0.4 millimeters. With guidance from researchers at the University of California, San Francisco, Abraham Lee, M. Allen Northrup, and Peter Krulevitch developed this micro-electromechanical device. As shown in Figure 8, the microgripper is like a tiny hand that surgeons can use to place clot-inducing agents to fill an aneurysm. A surgeon may also use it to perform minimally invasive *in vivo* biopsy or catheter-based endovascular therapy. Nonmedical uses include assembling small parts for manufacturing and remote handling of small particles in extreme environments, such as high or low pressures and hazardous fluids.

A key to the microgripper's effectiveness is a thin-film microactuator that is fabricated from a shape-memory alloy (SMA). At low temperatures, SMAs are easily deformed, but when heated, they recover their original shape. This reversible transformation forms the basis for shape-memory actuators, in which a biasing force, produced by a spring, for example, deforms the SMA element at low temperature, and the SMA element overcomes the bias when heated. For the microgripper, the team developed a sputter-deposited shape-memory actuator of nickel–titanium–copper, with a transformation temperature just above body temperature. The microgripper is inserted into a blood vessel in the closed (deformed) position. Through a thin wire connected to the microgripper, an electrical current of 0.1 milliamp activates the actuator, deflecting each arm up to 55 micrometers and returning the gripper to its undeformed (open) position. As it cools, the gripper will open again. (A patent was recently issued for another microgripper made of plastic with a balloon actuating system.

Lee, Julie Hamilton, and Jimmy Trevino have also built a low-leakage, high-efficiency microvalve (Figure 9). Effective microvalves are an important link in creating miniature total analysis systems that can be used for drug delivery and bioanalytical instrumentation. Nonmedical applications for the microvalve include fluid injection analysis, chemical processing and analysis, and atmospheric and temperature control equipment. In this design, an electrode is sandwiched between two polyimide films with different coefficients of thermal expansion. (Polyimide is a flexible plastic material.) Delivery of less than 1 milliwatt of power causes the "cantilever" to clamp down, sealing an etched hole beneath it.

And the Work Goes On

Two relatively new areas of expertise for the Microtechnology Center are treaty verification and counterproliferation, which require low-cost, efficient, autonomous processing of large numbers of chemical and biological samples. Integrated microdevices are critical to the success of these new fields.

Microtechnologies and microdevices have never been an end in themselves at Livermore. Rather, they are problem solvers. As Lawrence Livermore researchers search for solutions to mission-specific challenges, they often find that commercial products do not meet their needs. They turn to the experts at the Microtechnology Center, whose creations are often what enable a Laboratory experiment or diagnostic tool to function successfully. Integrated microdevices are thus finding their way into increasing numbers of Laboratory projects.

— Katie Walter

Key Words: bioanalysis, DNA analysis, DNA sequencing, flow cytometry, gas chromatography, microactuators, microdevices, microstructures, photonics, polymerase chain reaction, semiconductors, shape-memory alloys, thin films.

For additional information contact Ray Mariella (510) 423-3610 (mariella1@llnl.gov).

About the Scientist

RAY MARIELLA, JR., is head of the Microtechnology Center. For the last five years he has been a team leader for bioinstrumentation and the thrust area leader for microtechnology. Mariella joined Lawrence Livermore in 1987 as a project engineer in the Electronics Engineering Department's Engineering Research Division to establish a capability in molecular beam epitaxy. He received his B.S. in mathematics, chemistry, and chemical engineering from Rice University in 1969 and his M.A. and Ph.D. in physical chemistry from Harvard University in 1970 and 1973. Before coming to Livermore, he worked at the Allied Signal research facility in Morristown, Virginia. He has published more than 30 articles and holds 5 patents.

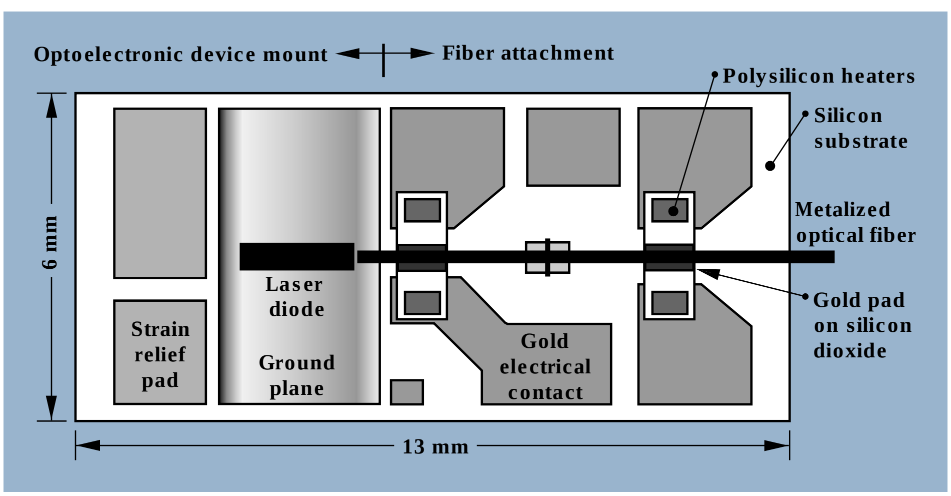
Silicon Microbench Technology

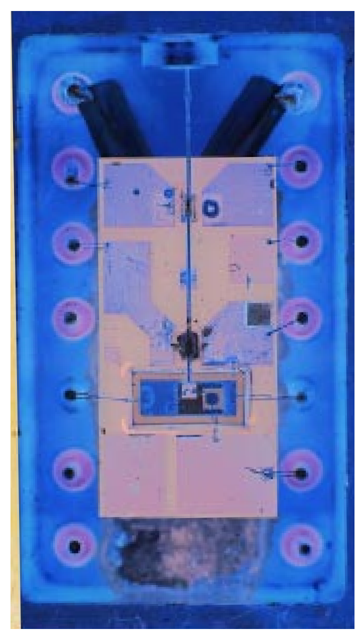
MOST fiber optic communication is now done at rates below 1 gigabit (1 billion bits) per second (Gb/s). The dimensions of the multimode fibers used at these rates allow component-alignment tolerances of several tens of micrometers. New communications standards are designed for operation well above 1 Gb/s. Such high speeds require that much finer single-mode optical fiber be used. This fiber must be aligned to single-mode optoelectronic components at submicrometer tolerances. Achieving these tight tolerances using current cumbersome manual alignment and attachment (pigtailing) techniques takes extraordinarily long times. These times drive up the costs of packaging, which can account for as much as 95% of the cost of optoelectronic devices. The most time-consuming and, therefore, most expensive part of the packaging is the alignment and attachment of the fiber. Today, each single-mode packaged device typically costs several thousand dollars.

We are developing automated alignment and attachment techniques to reduce the cost of packaged opto-electronic devices. Our mounts provide the stability and localized heating to achieve the tight tolerances while simplifying assembly and allowing relatively inexpensive mass production. Volume production is the key to reducing costs 10 to 20 times, to less than $10 a device for the packaging cost.

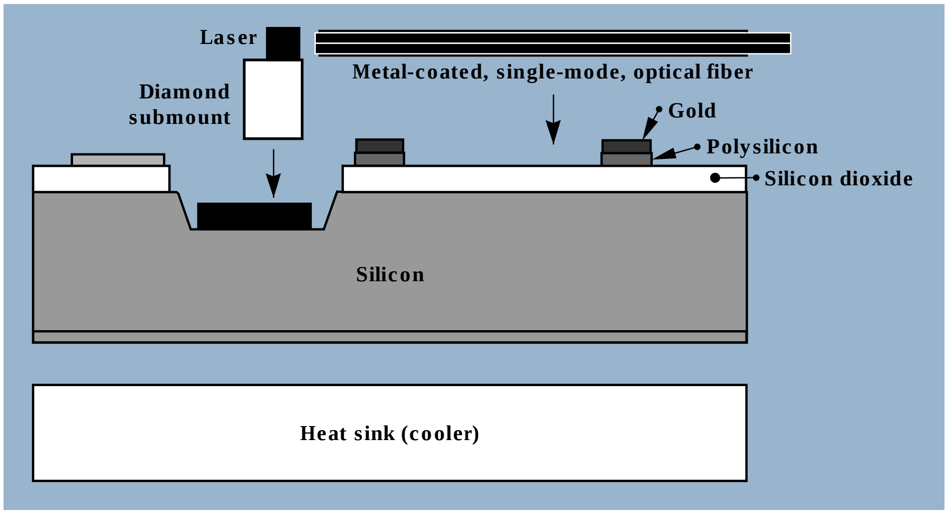
The key to mass production is to reduce the time per "pigtail"—the packaging operation of joining an optical fiber to an optoelectronic device, such as a laser. We are building a fiber pigtailing machine that will automatically align a fiber to a laser diode or to a lithium niobate modulator with submicrometer accuracy in less than 5 minutes. (At volumes of several thousand pigtails per year, the cost per manual pigtail approaches $100, whereas at volumes of several tens of thousands per year, the cost per automated pigtail is less than $10.) We designed and built silicon substrates with geometries that are compatible with the automated processes and have the stability required to maintain the submicrometer alignment tolerances necessary for single-mode operation. These substrates are the key part of an automatic alignment package.

We have designed our mounts with discrete areas for optoelectronic device attachment and areas for fiber attachment. For example, the 13- × 6-mm mount shown in the figure below is for packaging a 1550-nm distributed feedback





(above) Sketch of silicon mounts showing the location of the components and heaters. (right) Photomicrograph of a silicon mount inside a standard gold-plated metal package with a laser diode. A metalized optical fiber is mounted and aligned to the diode. The silicon mount is 6 ¥ 13 millimeters.



Cross section of a mount showing precision-etched well for laser diode to help vertically align the optical axis.

laser. On the left half, gold pads provide a ground plane for the laser and stress relief for the wire bonds. To attach the fiber on the right half of the mount, two polysilicon heating elements are connected to gold bonding pads for electrical contact. In the center of each heater, a 1- × 0.5-mm gold solder attachment base (on a layer of silicon dioxide for electrical isolation from the polysilicon heater) is large enough for a 125-μm-diameter fiber to be soldered to it. We use either 100-μm-diameter solder balls or solder paste to attach the metalized fiber.

A simple power supply and a timed switch allow us to control accurately the magnitude and time of the applied current, giving our prototype very reproducible performance. We use active feedback to align the fiber to submicrometer accuracies. While the fiber is held in the position that maximizes the optical coupling, current is passed through the heater to reflow the solder, which wicks around the metalized fiber without disturbing the automatic submicrometer optical alignment. Conventional techniques for melting solder heat the entire substrate, creating considerable difficulty with drift of the alignment after the solder has cooled and requiring such corrective measures as preshifting the fiber so that after cooling the thermal shifts will tend to bring the fiber into alignment. By providing only the small amount of heat needed to melt the solder locally, we avoid these thermal shifts and greatly simplify the alignment process. We observe no decrease in the light coupled from a 800-nm laser diode into the single-mode fiber after the solder has cooled.

Silicon mounts offer the additional benefit of allowing us to use standard, low-cost silicon etching techniques to bring the optical axis of different components in approximately the same line vertically (see figure above), minimizing the solder thickness and therefore thermal drifts and long-term creep that are problems with other packages that use thick solder or metal “shims” to bring the optical axis in alignment.

The potential market is enormous. As fiber communication products become more prevalent, one can envision these packages used at either end of every fiber for transmitters and receivers of high-speed optical signals. At sufficiently low production costs, the market is potentially many millions to billions of devices in a multitude of applications, ranging from single-mode fiber-optic communication products and laser-diode transmitters, to the assembly of hybrid optoelectronic multichip modules and fiber arrays, semiconductor optical amplifiers, fiber-optic gyroscopes, optical interconnects for computer backplanes, asynchronous transfer mode (ATM) switches, all optical switches, and optical modulator arrays.

Our mount geometries with on-board heaters allow rapid attachment of not only the fiber but other components as well. Using solders with different melting temperatures and attaching components farthest from heaters first allow sequential mounting of several components on the same silicon mount without melting solder and disturbing the alignment of previously attached components. Since many components do not require submicrometer alignment, we envision that an automated system could place and solder them onto the mounts in only a few seconds.

On-board heaters can be used in applications other than packaging laser diodes. For example, we are designing a longer mount with heaters at each end to pigtail both ends of a semiconductor optical amplifier. We are also investigating geometries compatible with high-speed applications in which on-board transmission lines will be needed to provide sufficient electrical bandwidth for the very high-speed optoelectronic devices.

For further information contact Michael Pocha (510) 422-8664.

Signal Speed Gets Boost from Tiny Optical Amplifier

DEMANDS on data communications systems are growing by leaps and bounds. Information travels faster and farther than anyone might have dreamed possible even 20 years ago, but still the Information Superhighway wants more.

Lawrence Livermore National Laboratory's Sol DiJaili, Frank Patterson, and coworkers have developed a small, inexpensive optical amplifier. It incorporates a miniature laser to send information over fiber-optic lines at a rate of more than 1 terabit (1 quadrillion bits of information) per second. The amplifier is about the size of a dime, which is 1,000 times smaller than comparable amplifiers, and in production quantities it will cost 100 times less than the competition.

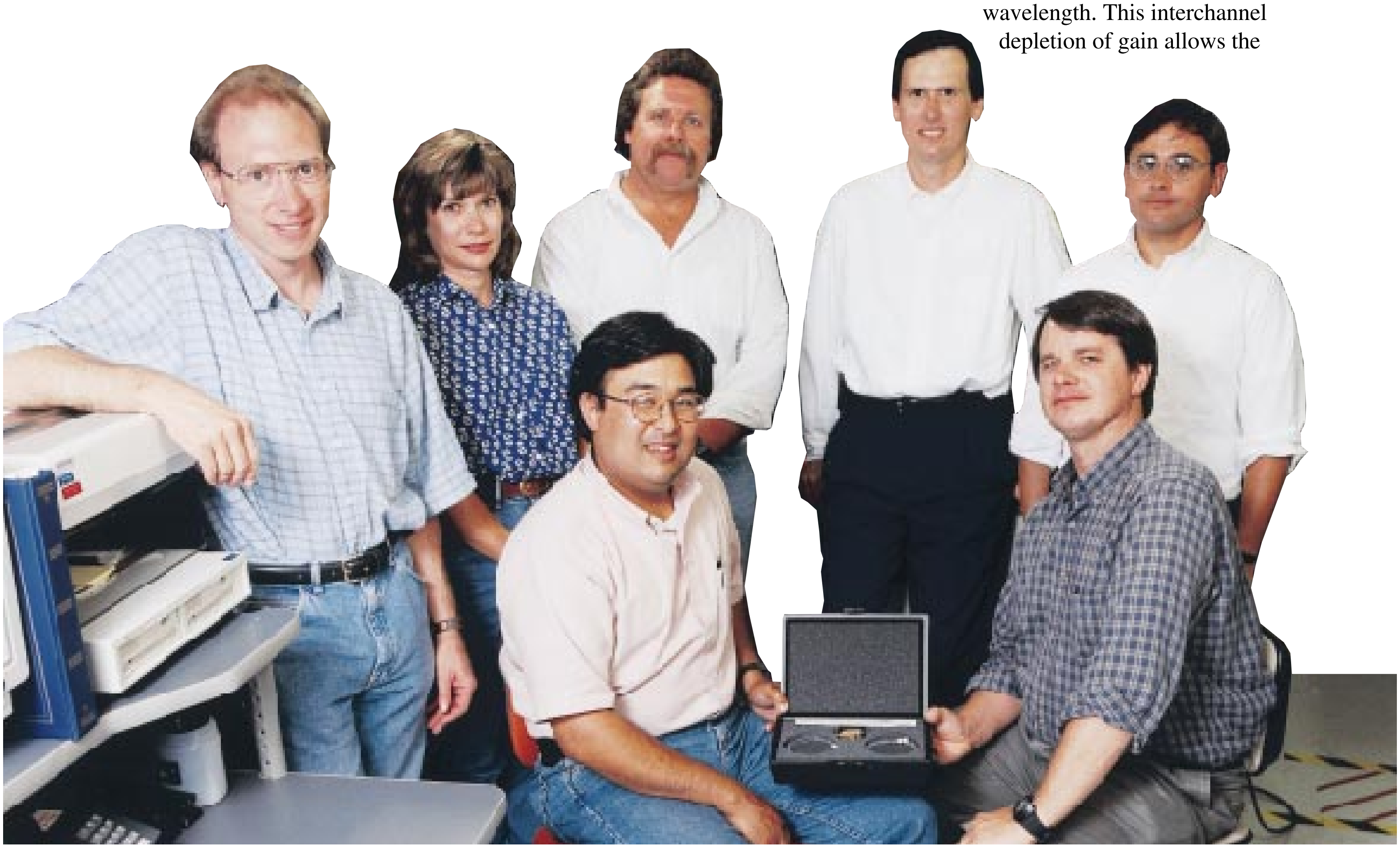
Fiber amplifiers can operate at comparable bit rates, but they are large and expensive, which limits their usefulness. For example, erbium-doped fiber amplifiers currently enable hundreds of thousands of simultaneous telephone conversations across continents and under oceans on a single fiber-optic cable. But their high cost makes them economical only for long-haul systems, and their large size means that they cannot be integrated easily with other devices.

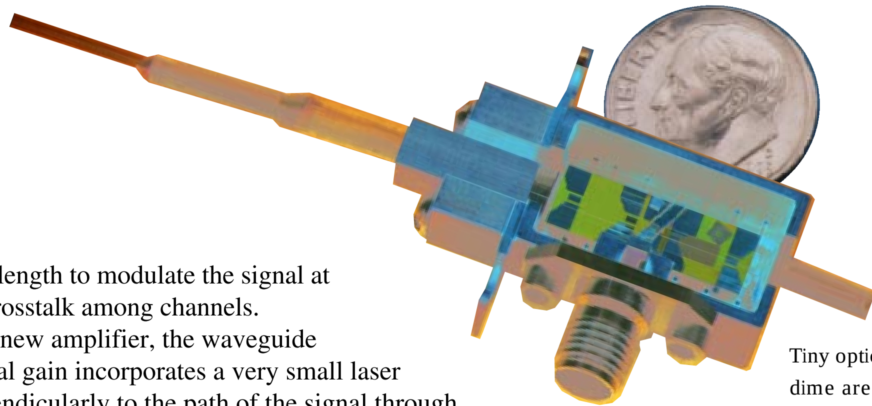
On the other hand, conventional semiconductor optical amplifiers are inexpensive and relatively small, but crosstalk and noise at high transmission rates limit their performance to about 1 gigabit (1 billion bits of information) per second or less.

The Laboratory's new amplifier combines the best of both worlds. Its small size, low cost, and high performance make it an excellent candidate for use in wide-area networks, local-area networks, cable TV distribution, computer interconnections, and anticipated new fiber-to-the-home applications that will require multiple amplification steps and therefore many amplifiers.

A Vertical Laser at Work

In a conventional semiconductor optical amplifier (SOA), the signal passes through a waveguide that has been processed directly onto a direct bandgap semiconductor. Inside the waveguide is a gain medium through which the optical signal passes and where the signal gains in intensity. The problem with these conventional SOAs is that the gain cannot be controlled, so signals tend to fluctuate. A signal at one wavelength can deplete the gain of a signal at another wavelength. This interchannel depletion of gain allows the





Tiny optical amplifiers about the size of a dime are inexpensive and have excellent performance for communications applications of the future.

signal at one wavelength to modulate the signal at another, causing crosstalk among channels.

In Livermore's new amplifier, the waveguide supplying the signal gain incorporates a very small laser that operates perpendicularly to the path of the signal through the waveguide. This "vertical cavity surface emitting laser," composed of a stack of cavity mirrors that are fabricated during semiconductor crystal wafer growth, replaces the standard gain medium of a conventional SOA.

This new laser amplifier takes advantage of some basic properties of lasers to reduce crosstalk by a factor of 10,000. In a typical laser, electrical current is introduced into the gain medium, which is situated between two sets of mirrors. Much too rapidly to be seen, the photons in the gain medium bounce back and forth between the sets of mirrors, constantly gaining in intensity. Because no mirror is perfectly reflective, some of the photons are lost through the mirrors during this back-and-forth process. But once the gain is equal to the losses or, put another way, equal to the reflectivity of the mirrors, the photons will begin to "lase."

A laser's gain thus has a cap. By introducing a laser into an SOA waveguide, the signal gain can be "clamped" at a specific level. Then, when signal channels at multiple optical wavelengths pass through the waveguide, there is virtually no crosstalk across the independent optical channels.

The lasing field also affects the recovery time of signals through the waveguide. After every "bit" of the optical signal passes through the gain medium, the medium requires a short recovery time before it can accept the next bit. This gain recovery time in a conventional SOA is typically a billionth of a second. Attempts to push the amplifier to faster bit rates than the gain medium can accommodate often result in one bit depleting the gain of the subsequent bit, which is another form of crosstalk. The introduction of a lasing field prompts the medium to recover much more quickly, on the order of 20 trillionths of a second. This means that the amplifier can successfully track the amplification of a serial bit stream at very high bit rates.

Team members sharing the award for the miniature optical amplifier include (from left, front) inventors Sol DiJaili and Frank Patterson; (rear) fabrication techs William Goward and Holly Petersen, program leader Mark Lowry, and inventors Jeff Walker and Robert Deri.

A New Ubiquitous Amplifier?

This new amplifier is truly the optical analog of the electronic amplifier, the electronics industry's ubiquitous workhorse. Because the new amplifier relies on standard integrated circuit and optoelectronic fabrication technology, it can be incorporated into many different types of photonic integrated circuits.

In the near term, because this amplifier puts SOA performance on a par with fiber amplifiers, it could be used as a replacement for or complement to fiber amplifiers in long-haul communication networks.

Looking farther into the future, if tiny, inexpensive optical amplifiers provide the broad signal bandwidth needed to transmit visual images as well as computer data, many people may someday work in "virtual offices" in their homes. Via two-way video, they will be able to confer with colleagues, participate in meetings, and hear the latest company news without commuting to work. Two-way, high-resolution, panoramic video will also facilitate remote learning with a teacher in one place and one student or hundreds of students in another.

These kinds of applications, involving many individual users, will require an enormous number of amplifiers for signal propagation and distribution. Livermore's new laser optical amplifier could well become ubiquitous.

Key Words: fiber-optic communications; semiconductor optical amplifier; photonic integrated circuit; R&D 100 award; vertical cavity surface emitting laser.

For further information contact
Mark Lowry (510) 423-2924 (mlowry@llnl.gov),
Sol DiJaili (510) 424-4584 (dijaili@llnl.gov), or
Frank Patterson (510) 423-9688 (fpatterson@llnl.gov).

Speeding the Gene Hunt: High-Speed DNA Sequencing

FAST. Faster. Fastest. In the commercial arena, getting big jobs done fast requires automation, For the Human Genome Project at Lawrence Livermore National Laboratory, the key to uncovering thousands of yet-to-be-identified human genes is to automate and speed up the specialized biotechnical equipment that prepares and sequences DNA samples.

The point of all this urgency is the gold mine of information contained within the structure of the genes themselves. Genes and the proteins they produce hold the key to unlocking the mysteries of genetic diseases. Once the genetic code for a disease is understood, researchers can begin developing gene and drug therapies for that particular disease. The ultimate goal of the worldwide Human Genome Project is to find all the genes in the DNA sequence, develop tools for using this information in the study of human biology and medicine, and improve human health.

Sequencing involves determining the exact order of the four individual chemical building blocks, or bases, that form DNA. The total DNA in a single human cell has approximately 3 billion pairs of the chemical building blocks adenine, thymine, guanine, and cystosine.

For a multidisciplinary team of engineers, chemists, computer scientists, and biologists at Livermore, Joe Balch is project leader for developing a next-generation instrument for sequencing DNA. When this high-throughput DNA sequencer is built and its operating conditions are optimized, it will ultimately read nearly 600,000 bases per eight-hour shift, about 12 times faster than current instruments, which manage at most 48,000 bases per shift.

"There is a worldwide push in the field to 'pick up the speed' with which DNA is sequenced," said Balch. "The current strategy is to do it with existing technology and just turn the crank a lot of times with more people. It's very people-intensive. The next-generation sequencing machine we are developing will allow us to leave the old technology behind and take the next step in automation." Livermore expertise in microfabrication, bioinformatics, and biochemistry makes this move possible.

Faster sequencing will also provide other Livermore programs with faster access to information in nonproliferation projects to detect biological signatures of collected samples and in bioremediation projects to optimize micro-organism action.

Figure 1. Computer-generated image of fluorescent bands after the fragments are detected by the laser.

Sequencing: How It Works

When biological researchers want to sequence a section of DNA, they clone fragments of that section and then run four nearly identical reactions on those fragments. In these reactions, the four bases are chemically labeled with four different fluorescent dyes.

The sequencing machines currently used at the Laboratory are based on a gel-electrophoresis system, which works like this. The DNA samples are loaded by hand into a 200- to 400-micrometer-thick polyacrylamide gel, rather like thin Jello, which is sandwiched between two large glass plates, 48 centimeters long by 25 centimeters wide. The plates can hold 36 samples at a time. An electric current is then applied to the gel, and, because the DNA itself has a negative charge, the fragments migrate in 36 columns or "lanes" from the top to the bottom of the plate. The DNA fragments move at different rates depending on their size: smaller ones move faster than larger ones. As the fragments migrate past a certain point in the gel, a laser beam scans back and forth across the plate, exciting the dyes on the DNA bases. As the fragments pass the laser, the bases are separated from smallest to largest. The fluorescent signals generated by the laser are detected by photomultiplier tubes (or other detectors), and a computer captures, stores, and processes them (Figure 1).

When cleaning, loading, and running times are all taken into account, it takes between five to seven hours to complete a run.

Each sample contains about 500 bases, which means each run of 36 samples yields no more than 18,000 bases. According to Balch, conventional technology is expanding the number of lanes to 64, which will increase the yield to about 32,000. But to increase those numbers significantly, say, by an order of magnitude, requires applying some new technologies.

There are a number of ways to increase this yield, explained Balch, who is also the former head of the Laboratory's Microtechnology Center. "You can increase the number of lanes on a single run. You can increase the speed at which you do a run—in other words, apply more electric field to the fragments. You can also look for ways to cut down on the loading and cleanup times, which often take a couple of hours. But to do all of these things, you need to move outside the current technologies and look for different ways to get the job done." That is what they are doing for their new sequencing machine (Figure 2).

Increase the Lanes

In the current system, although the samples travel in "lanes," no physical barriers divide one lane from the next. "And even though you have an electric field pulling the fragments to the bottom, they still wander a bit," said Balch. "Right now, we correct the wandering with software, with what is called 'lane tracking.' But if we start packing more lanes in, there's a problem with the columns blurring into each other."

So Balch and his team are taking a different tack: fabricating small, exact lanes, or microchannels, in large glass plates through which the gel medium flows. This effort got its start in 1993 with seed money from the Lawrence Livermore's Laboratory Directed Research and Development Program. In 1994, the Laboratory entered a year-and-a-half agreement with Perkin Elmer's Applied Biosystems Division

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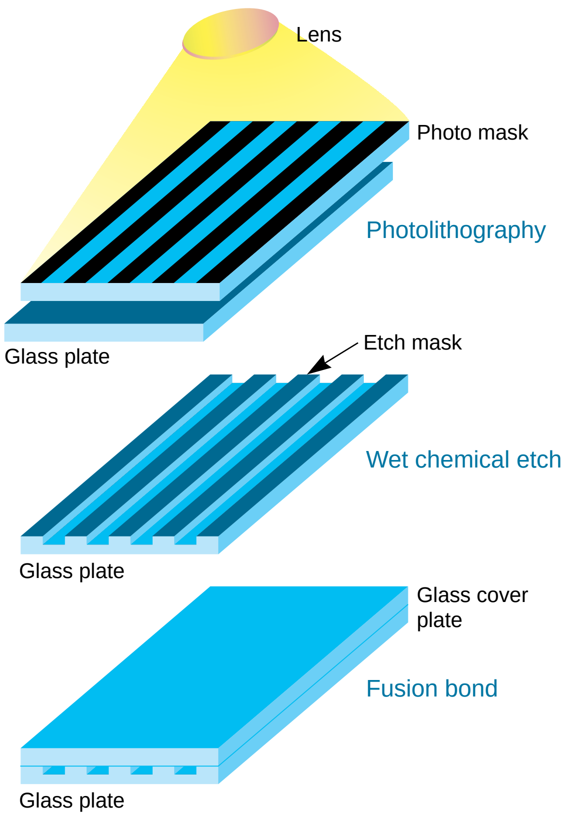

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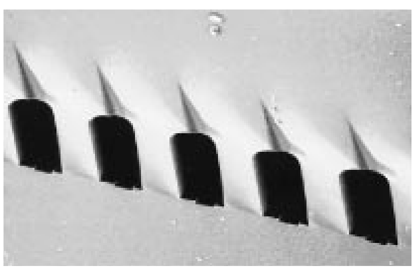

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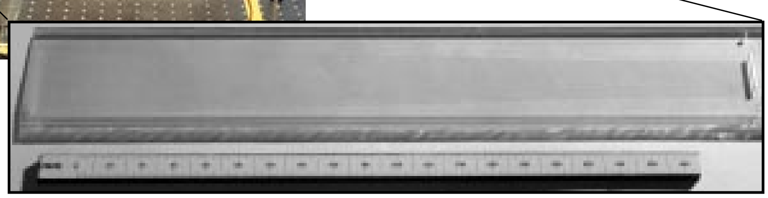


Figure 2. During fabrication of the new 96-lane sequencing machine, the pattern of channels is first defined by (a) photolithographic processing on a photoresist plate. (b) Then, that plate is used to chemically etch the pattern on the glass. (c) Finally, the top piece of glass is bonded to the etched glass plate.

to further develop this technology and some of the others needed for the new system. This effort is now being supported by grants from the National Institutes of Health and the DOE Human Genome Project.

Last year, Steve Swierkowski and Courtney Davidson of the Microtechnology Center successfully demonstrated the fabrication of a 96-lane array on a piece of glass 7.5 centimeters wide and 55 centimeters long—in other words, twice the lanes that current technology can offer in less than a third of the space. Ultimately, the team will be producing plates with 384 channels.

"These high-density microchannel glass plates are the really novel piece of our instrument," noted Balch. "The fabrication process involves three steps, each of which we need to continue to build and improve upon." (See Figure 2a.)

The first is the photolithography step, where the pattern of the channels is defined on a photomask plate. The second involves using that plate to chemically etch that very small pattern on the glass to very exact specifications. The final step is bonding the top piece of glass to the etched glass plate. Figure 2c shows the current prototype instrument developed by Davidson, Larry Brewer, Joe Kimbrough, and Ron Pastrone.

Increase the Speed

Another way to speed up the process is to increase the electric field. The velocity of the DNA increases proportionally. In the current system, however, just increasing the field leads to other problems.

A higher electric field increases the power dissipation, which increases the temperature in the sieving media, explained Balch. And when the gel heats up—and the DNA samples in it—thermal diffusion causes the fluorescent bands to spread out. The bands run into each other and can no longer be identified as individual and distinct bands. This problem can be significantly reduced by using a very thin gel (about 50 micrometers thick) or other sieving media in place of the polyacrylamide gel now being used. The thinner gel means that the temperature gradient across the width of the gel is smaller, and the thermal diffusion of the DNA fragment bands is less.

With this thin sieving media, the instrument can run with an electrical field three to four times higher than that used on the conventional instrument. Thus, the speed of the run increases by the same factor.

Decrease the Clean-Up Time

Another improvement involves using small syringe pumps to inject thin sieving media into the microchannels of the new instrument when a run begins and then automatically pumping it out when a run is complete. This procedure will significantly speed up the overall time it takes to complete a run.

"With the polyacrylamide gel now in use, you have to go through a lengthy preparation at the start of a run to make a fresh gel. Then at the end, you have to take the plates apart, remove the old gel, and clean the plates for the next run. With this new media, we just pump it in and out through channels and capillaries without removing the microchannel plate from the instrument," said Balch. "We figure that when the system is up and running, one run will take two to three hours from start to finish, compared with four to five hours using the polyacrylamide gel."

Putting It All Together

Because the new system has different performance specifications than the old, simply loading the new glass plates with the new medium into the old machine is not the only change.

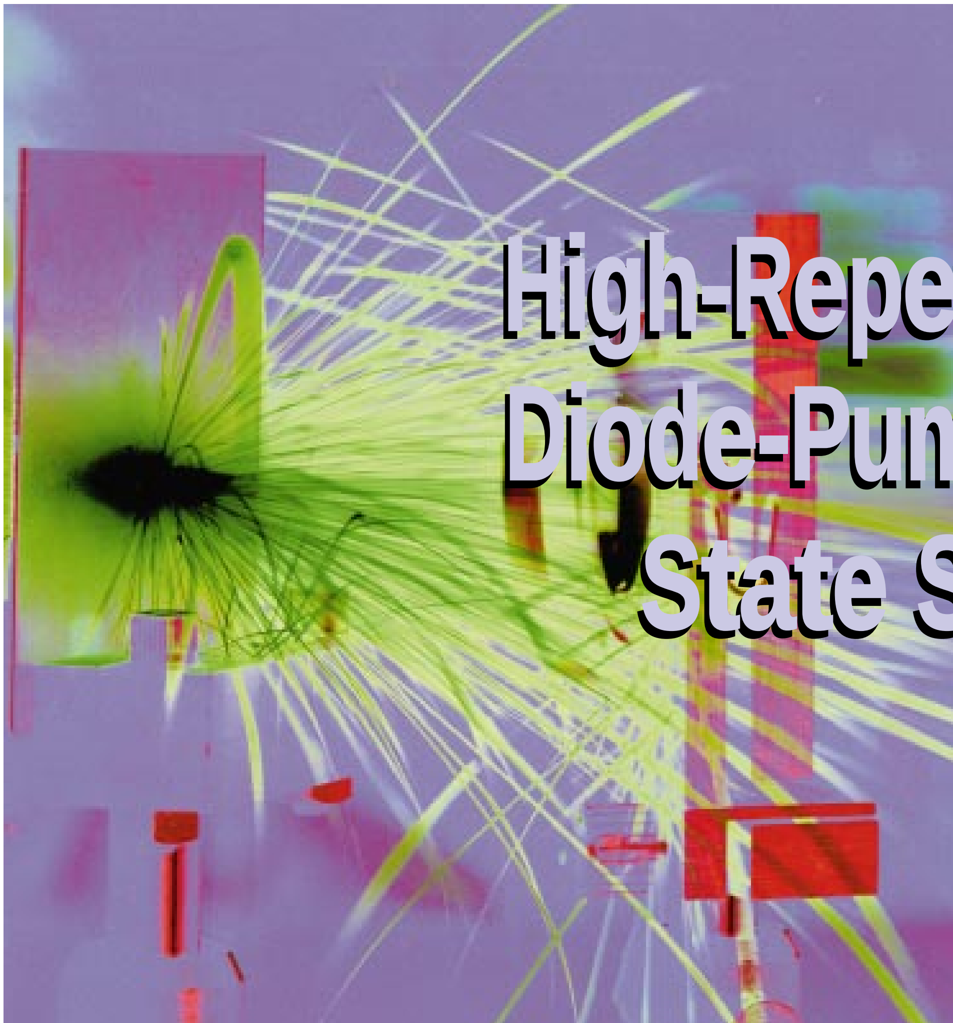
For instance, because the DNA fragments are moving at a higher velocity when they come to the laser, the laser has to scan across the plates faster. In addition, given the 96 lanes now and the 384 to come in the future, Balch and his team are exploring several concepts for automatic sample loading.

Other systems being developed include the laser-induced fluorescent detection system, the fluidic and pumping system for the polymer medium, a temperature control system, and analysis software. "These improvements plus the microchannel plates themselves add up to seven major parts of the high-throughput DNA sequencer that we must eventually meld together," said Balch. "The final production system is still down the road. When it's ready, we plan to make it available to others within the Department of Energy and the human genome community."

— Ann Parker

Key Words: DNA sequencing, Human Genome Project, microchannel, polyacrylamide gel.

For further information contact Joe Balch (510) 422-8643 (balch1@llnl.gov). The Human Genome Center's Internet home page is at http://www.llnl.gov/bbrp/genome/genome.html. The Department of Energy's "Primer on Molecular Genetics" is located at http://www.gdb.org/Dan/DOE/intro.html.



High-Repetition-Rate, Diode-Pumped, Solid-State Slab Lasers

Microchannel-cooled laser diode bars, a new slab laser geometry, and several new laser host materials have made possible a new average-high-power laser system that is suitable for a range of applications.

SINCE their earliest work on rod lasers, researchers have recognized that beam focusing and depolarization in isotropic laser media severely limit the average-power capabilities of the laser output beam. The cause of this limitation is the radial heat flow that results when a rod is heated throughout its volume but cooled at its surface. In the 1960s, researchers in the Soviet Union and at General Electric developed the slab laser in an attempt to mitigate these restrictive thermo-optical effects. The slab laser was an improvement on the rod laser in that it had a better output beam, but it still had residual beam distortions that were too large for many applications and a lower than hoped for efficiency. It was also sufficiently complex to discourage widespread interest in its potential use. In the early 1980s, the slab laser drew renewed attention, and researchers at Stanford University, LLNL, and other institutions began a move toward improving solid-state slab laser technology.

By the mid-1980s, researchers at LLNL recognized that diode-pumped slab lasers had several advantages over flashlamp-pumped slab lasers: they were smaller, lighter, more efficient, and more reliable. Nevertheless, diode-pumped lasers still had one primary disadvantage—they operated at a relatively high cost per average watt of output power.

For the last few years, LLNL's program for advanced laser research has been working to produce a design that overcomes this cost barrier and at the same time provides a variety of performance characteristics. Thus, in addition to developing high-energy drivers for laser fusion and high pulse-repetition-frequency sources for uranium isotope separation, we have begun developing high-energy devices for other applications. One of our most recent devices is a high-power, continuous-wave, or high-duty factor, laser diode package with a low-cost, microchannel-cooled silicon submount. This technology, together with a new slab laser geometry, has made possible the development of a high-average-power, diode-pumped, solid-state laser system that is suitable for a range of applications.

Pumping with Laser Diodes

Laser diodes are almost the ideal pump source for solid-state lasers since essentially no radiation is emitted outside the absorption bands of the active medium and the heat deposited per inverted active ion is almost an order of magnitude less than it is for flashlamp-pumped systems. Figure 1 illustrates the advantages of pumping a solid-state neodymium-doped glass slab laser with laser diodes rather than flashlamps. The diode pump emits directed narrowband radiation that spectrally overlaps the 800-nm pump band of neodymium. Thus, the efficiency of transport to and deposition of radiation in the solid-state gain element is several times higher than that achieved by flashlamps since flashlamps emit broadband radiation into 4π steradians. Because of their directional emission, diode lasers can be efficiently coupled into a solid-state laser gain element via multimode fibers, keeping the pump and power-conditioning equipment remote from the laser head and work area.

Because the diode bar excites a neodymium pump level that lies only slightly above the upper laser level, the density of waste heat generated is a fraction of that produced by flashlamps for the same gain. This drastically reduces the amount of external cooling required and permits the design of lasers with near-diffraction-limited output beams. The exceptionally long operating life of modern diode-pumped lasers—tens of thousands of hours, billions of shots—far exceeds the operational life of a continuous-wave or pulsed flashlamp-pumped laser able to produce the same output power.

Removing Heat from a High-Average-Power Laser Diode Bar

Semiconductor-pumped lasers are inherently efficient optical sources capable of generating high-peak optical powers from compact sources. In fact, electrical-to-optical conversion efficiencies of greater than 50% have been reported.[1] In spite of these high efficiencies, the average-power operation of a laser diode bar is limited because of the waste heat it generates. The following example illustrates this problem.

Consider a 1-cm-long diode-array-bar that generates 60 W (peak) of optical output power at a 40% electrical-to-optical efficiency. If such a bar is to be run continuous wave, the waste heat it generates (in this case 90 W) must be carried away through an area corresponding to the footprint dimensions of the bar. Typically, these footprint dimensions are on the order of 500 μm by 1 cm, giving a footprint area of 0.05 cm^2. Thus, the heat flux that must be drawn off the bar is 1.8 kW/cm^2. Such heat flux is extremely high[2] and is more commonly associated with the internal structure of a rocket engine nozzle in ballistic entry than with electro-optical devices (see Figure 2). Such high heat flux usually occurs in environments of several thousand degrees centigrade or more; this is not good for laser diodes, which require environments at or near room temperature to operate efficiently and reliably.

Thus, the combination of the high heat flux generated by laser diodes and the low temperature required for their operation make the design and implementation of a diode-array heat sink a very challenging problem. Our solution has been the development of a compact, modular heat sink for high average-power operation of the laser-diode bars used to excite rare-earth-doped crystalline lasers.

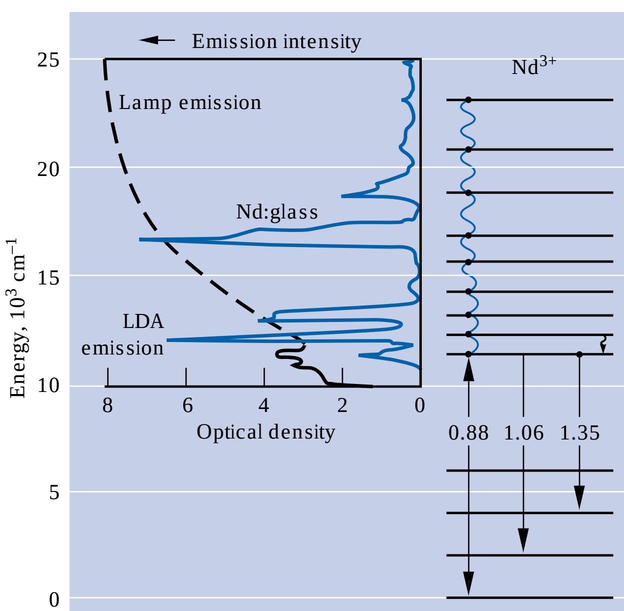


Figure 1. Characteristics of diode-laser and flashlamp pumping for neodymium-doped solid-state slab lasers.

Two-Dimensional Microchannel-Cooled Diode Arrays

Figure 3 is a photograph of our first-generation diode-array heat sink, a modular diode package that uses water and silicon-etched microchannels to achieve the thermal performance necessary to cool the laser diode bars. (The box on p. 20 explains how we fabricate these bars.) These packages are most efficient when we use low-cost silicon as the chip-carrier material and silicon-etching technologies to fabricate the microchannels.

The package itself is approximately 2.0 cm on a side and can accept up to 1.8 linear cm of diode array material (visible along the bottom edge of the package, shown in Figure 3). The elongated holes visible in the photograph serve as the water inlet and outlet for a complicated system of feeder plenums and channels that are micromachined into the interior of the package. Large radiating surfaces (two-dimensional arrays of laser diodes) are built up from this modular package by stacking units one on top of another, i.e., by using "rack-and-stack" architecture. Stacking the packages (modular construction of the heat sink) allows for large two-dimensional apertures. In such arrays, we can exchange individual packages easily and quickly. Figure 4 shows a two-dimensional array in operation.

Packaging the Diode Pump

In constructing these large two-dimensional arrays, we insert a conductive silicone rubber gasket, with the same hole pattern as the package, between individual packages to ensure hydraulic integrity and to provide electrical continuity from package to

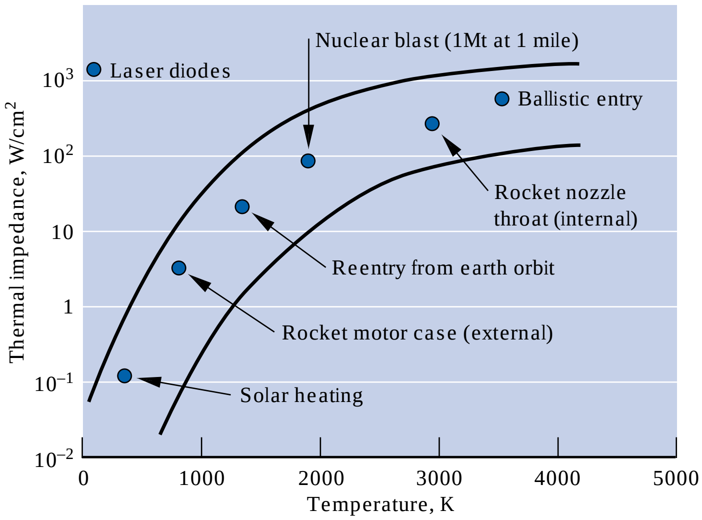


Figure 2. Thermal impedance requirements of 0.01°C/cm²/W present a stressing problem in thermal management.

(a)

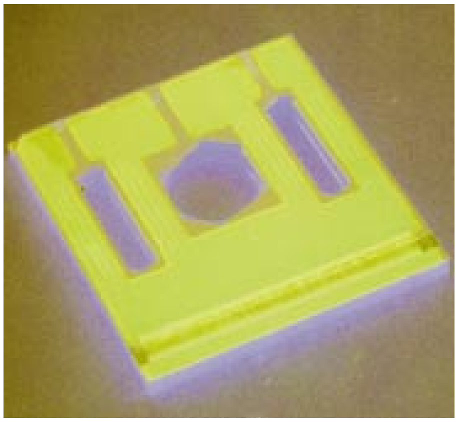


Figure 3. (a) A modular microchannel-cooled diode package. The package accepts 1.8 cm of laser diode bar. Its approximate dimensions are 2 cm by 2 cm. The diode array is mounted approximately 1.5 mm back from the top edge of the package and emits upward at grazing incidence to the metalized silicon cooler. The central through-hole is for a bolt that allows modules to be stacked in two-dimensional arrays. The elongated holes on either side serve as water inlet and outlet. (b) A cutaway drawing of the package showing placement of the conductive silicone rubber gasket.

(b)

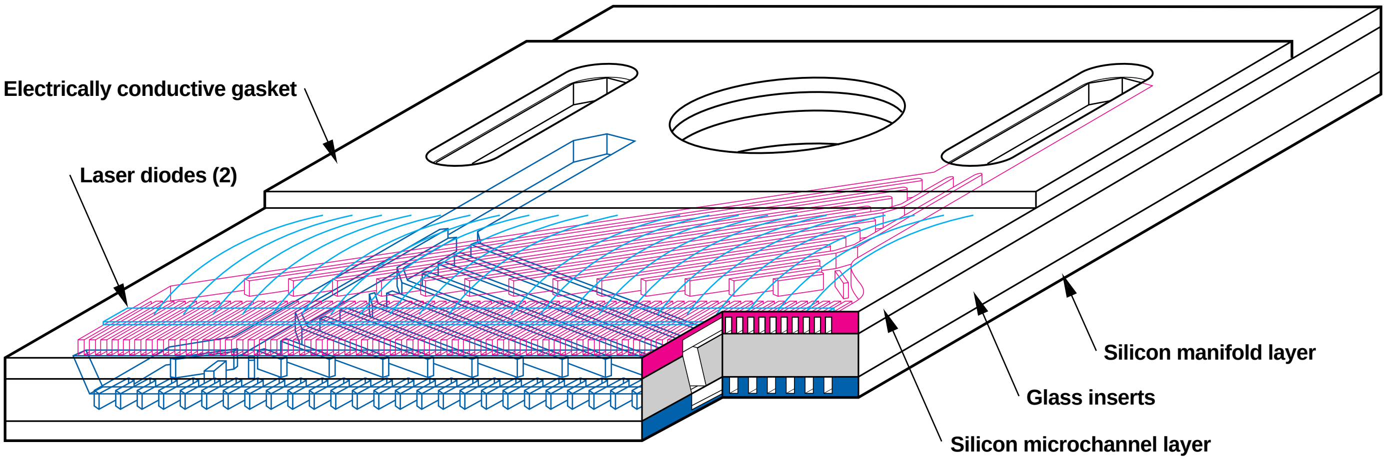
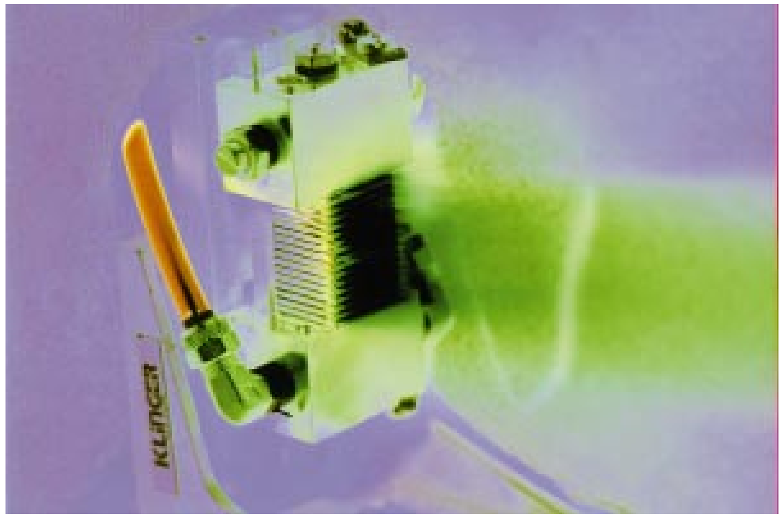


Figure 4. A two-dimensional microchannel-cooled laser diode array in operation. We construct the array by stacking 16 modular silicon-etched microchannel packages.

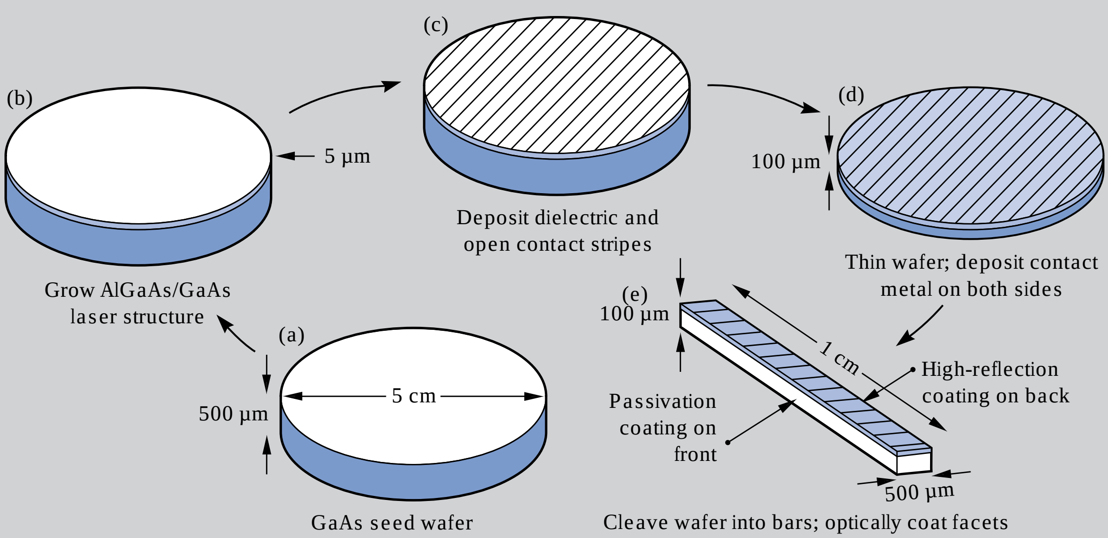


Fabrication of Laser Diode Bars

To fabricate our laser diode bars, we use a vendor-supplied gallium arsenide (GaAs) substrate, or seed wafer, that is typically 50.9 mm in diameter and 0.5 mm thick. We grow several thin crystalline layers on the substrate by metal-organic chemical vapor deposition (MOCVD). These layers are the diode structure. In MOCVD, gases containing atoms of the desired crystal constituents, such as gallium and arsenic, pass over the heated substrate, where they thermally decompose. The free constituent atoms contribute to the growth of a crystalline layer on the substrate surface. A typical laser diode structure consists of seven layers, each of which is unique in its composition. The layer thicknesses range from a few micrometers to 10–2 μm (about 33 atomic layers).

After growing the crystalline layers, we continue fabrication with the deposition of a thin insulating layer—typically silicon dioxide—on the grown layers. Then, using standard semiconductor photolithography techniques, we open thin stripes in the insulator to define the regions of the wafer for electrical contact. Next, we thin the wafers from the substrate side to a thickness of 100 μm, using a combination of mechanical lapping and chemical polishing. Thinning the wafers makes it easier to cut them into bars. We then deposit metals on each side of the wafer to guarantee good electrical contact.

At this point, the wafer is cleaved into bars that are typically 1 cm by 500 μm by 100 μm. The 500-μm dimension defines the laser cavity length, and the cleaved facets act as mirrors. In the final step of fabrication, we coat the front and back mirrors for low and high reflectivity.

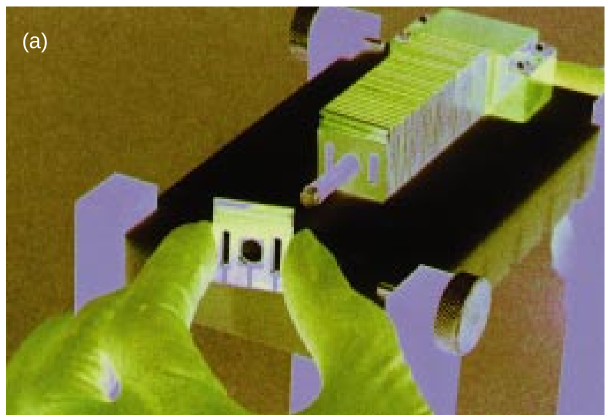


package. Figure 5a shows a large stack being assembled, and Figure 5b shows the finished stack. Each stack has a single water inlet and a single water outlet to minimize the number of hydraulic connections that must be made. Electrically, each stack is a series connection with one end serving as the positive electrode and the other as the negative electrode. The ease with which our modular approach has allowed maintenance on these stacks is largely responsible for the success of our diode effort.

An individual package, such as the one shown in Figure 3, actually consists of three layers in a silicon-glass-silicon sandwich configuration. Figure 6a shows these three layers. The top layer of silicon supplies water from the inlet port to the etched microchannels just below the laser diode bar, as shown in the cross-sectional view of Figure 6b. The central glass insert is slotted and has through-holes that match the silicon layers. These features are fabricated with an ultrasonic machining technique. The slot running parallel and close to the front of the glass piece drains the microchannels and delivers the water to a system of plenums in the bottom piece of silicon. This system, in turn, directs the water to the outlet port.

Figure 7 is a scanning electron micrograph showing a cross-sectional view of the microchannels in the top piece of silicon, just below the laser diode bar. The channels are nominally 25 μm wide, on 50-μm centers, 150 μm deep, and 4 mm long. This finned structure and the laminar flow of water through it account for the package's unique cooling capability. Heat flows up from the bottom through the bulk silicon and into the fins, where it is transferred into the flowing water. Once the heat is in the water, it is simply swept away by the continual flow of fresh cooling water into the channels.

Currently, we can produce up to 16 individual diode packages per day. The excellent thermal performance of the heat sink enables high-duty-factor operation of fully filled linear diode arrays at high-average power. Laminar-flow microchannel cooling is efficient in terms of the power needed to drive the coolant through the channels and is therefore an attractive, low-cost technique for use in diode-pumped, solid-state lasers.



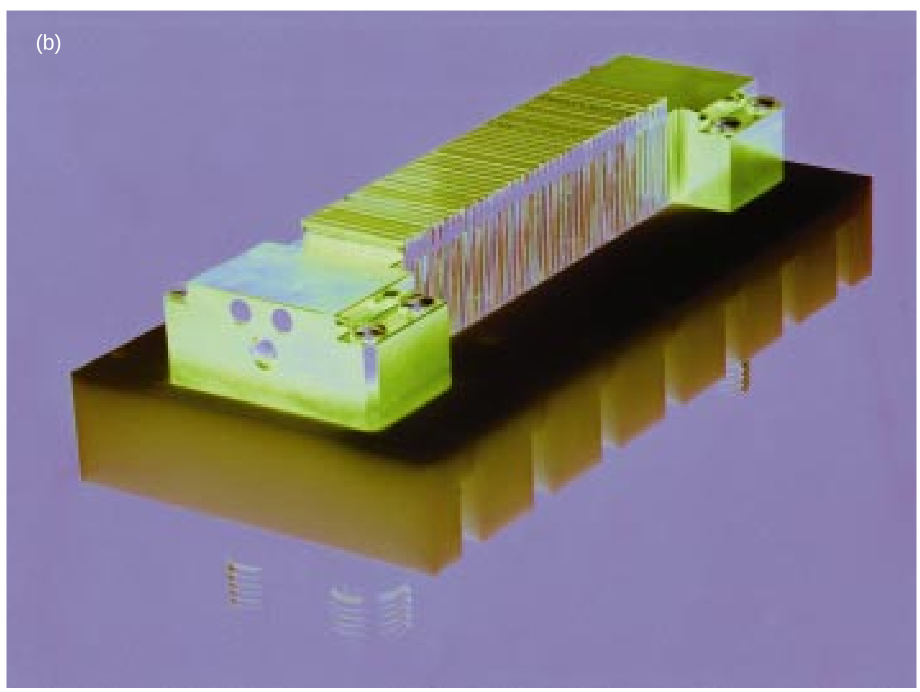


Figure 5. (a) A two-dimensional microchannel-cooled laser diode array being assembled. (b) This 42-module stack was fabricated for pumping a Nd3+:YAG high-average-power crystalline slab laser.

These diode packages are suitable for use in crystalline solid-state lasers because they afford the thermal control necessary to match the stringent temperature requirements placed on diode arrays that must couple to the nanometer-wide absorption features characteristic of lasing ions in crystals. Finally, these packages enhance high-average- power reliability through the low-temperature operation of the heat sink.

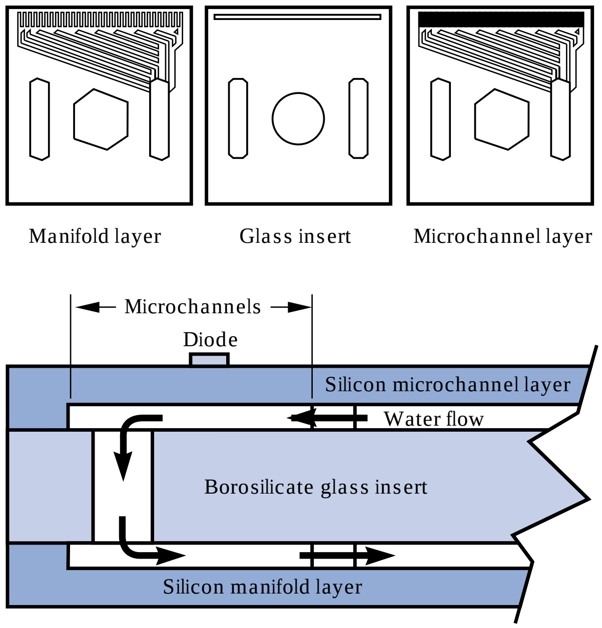


Figure 6. (a) The three-layered, microchannel-cooled module. A 787-μm-thick borosilicate glass insert with through holes is sandwiched between two pieces of 381-μm-thick etched silicon—the manifold layer and the microchannel layer. The central round feature and two elongated features on the silicon layers are through holes. The remaining patterned features are etched to a depth of approximately 150 μm. (b) A cross-sectional view of the three layers showing the water-flow path.

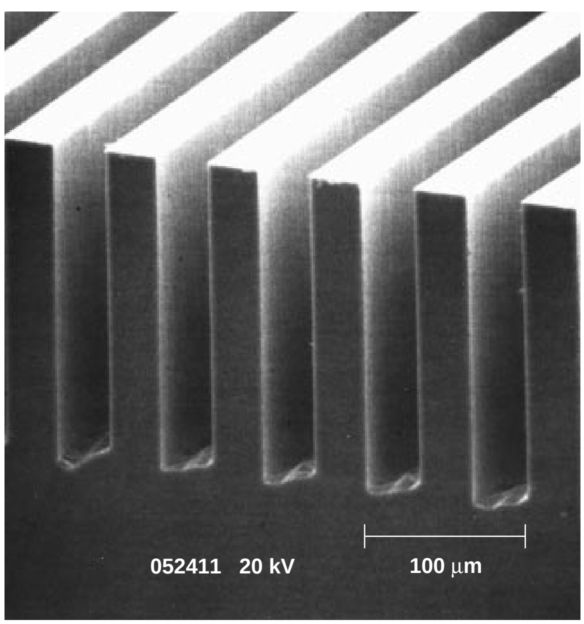


Figure 7. Scanning electron micrograph showing a cross-sectional view of the silicon-etched microchannels. The channels and separating walls are both approximately 25 μm wide. Channel depth is about 150 μm.

Slab Laser Geometry

Figure 8 shows the geometry of a diode-pumped slab laser with perpendicular ends. The slab is pumped and cooled from the x,z planes (the pump faces). Pump absorption and heat flow in the y direction cause large gradients in the medium optical properties along the y axis, and we assume uniformity in all other directions. By zig-zagging the optical beam between the pump faces as it travels down the z direction, we should be able to provide the same optical path length for all rays, regardless of their launch position in the x,y entrance plane.

This particular geometry provides some substantial advances for small crystalline-medium slab lasers:

- It produces the smallest beam distortions yet observed—they are below the measured sensitivity for even the highest output power achievable. Our models predict this behavior correctly, and we have therefore designed a laser that should be capable of operating above 1 kW in a very near-diffraction-limited beam.
- The beam travels through the medium twice for each pass through the laser cavity, which enhances the extraction dynamics of the laser. Thus, the overall achievable extraction efficiency is higher, and Q-switched pulse durations are shorter. The higher gain allows fewer passes to saturation in a regenerative amplifier architecture.

There is, however, a price for these advances: the beam path is clearly more susceptible to the onset of parasitic oscillations (i.e., lasing between surfaces other than the laser mirrors) than it would be in a slab with prismshaped ends. Parasitic gain depletion limits the energy storage in the slab because of the high refractive index at its ends. This makes it impossible to find an elastomer-based bond to decouple edge-cladding stresses in the slab and suppress parasitic lasing. Fortunately, the extremely high repetition rates allow small, single-shot energy storage and still provide considerable average output power.

Diode Pump and Laser Slab Working Together

Figure 9 shows the diode-pumped Nd:YAG (neodymium-doped yttrium-aluminum-garnet) slab laser we have built and used as a test bed for our new diode-pump technology. The slab lies between two arrays of 42 microchannel-cooled diode packages per side. The zig-zag laser cavity is formed by two external mirrors and the highly reflective mirror on the back of the YAG slab. The external mirrors are 20 cm from the transmitting crystal face. The folded zig-zag optical path traces a three-diamond-shaped pattern in the slab. All of the external mirrors used have a radius of curvature of 75 cm.

On the basis of our temperature-tuned, diode-laser absorption studies, we expect 80% or better absorption of our pump light over a diode coolant temperature range of 10°C. The spatial distribution of absorbed power across the width of the slab varies considerably over this 10°C range.

The diodes are driven using 100-μs, 140-A current pulses and repetition rates up to 2.5 kHz. The resulting Nd:YAG laser pulse is 80 μs long. Analysis shows a cavity loss of 4% at a 10-Hz operation.

Operating at 2500 Hz in the zig-zag configuration, the diode arrays have generated 1000 W of average power—which is the highest average power for a diode-pumped, solid-state laser reported to date. The optical-to-optical conversion efficiency is 23%.

Figure 10a shows the tilt-subtracted wave-front contour plot of a Mach-Zehnder interferogram of the fully pumped Nd:YAG slab as it is viewed along the zig-zag path. We observe less than one-fifth of a wave fringe distortion (1.06 μm) through the thickness. Compare the interferogram of the unpumped slab (Figure 10b), which shows about the same amount of fringe distortion. Clearly, the pump-induced part of the fringe pattern is better. At the present surface heat flux of about 8 W/cm^2 (for 300 W of output), this is the smallest fringe distortion across the slab thickness achieved so far.

In our future work with this laser, we plan to exploit the intrinsic beam quality. We will use an unstable resonator to extract beams that are less than 1.5-times diffraction-limited and hence can be focused at power densities that are almost within a factor of two of the theoretically achievable limit.

Applications for New Diode-Pumped Laser Systems

Microchannel-cooled laser diode bars and new laser host materials make

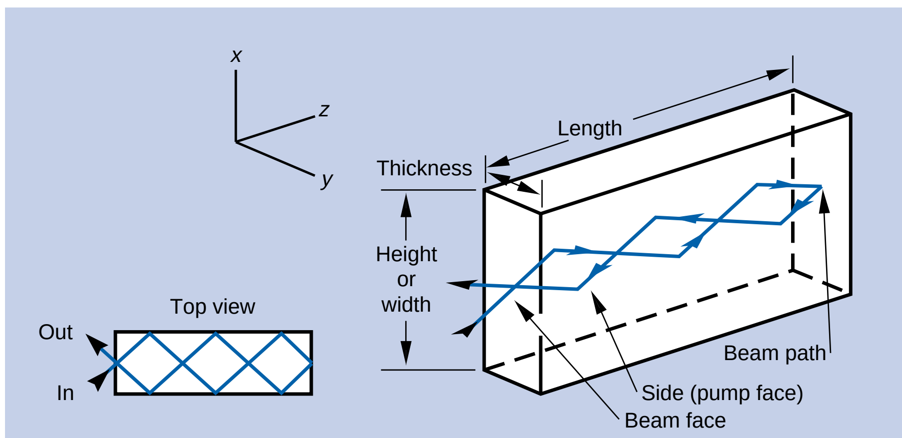


Figure 8. Slab laser geometry showing the zig-zag optical beam between the side pump faces.

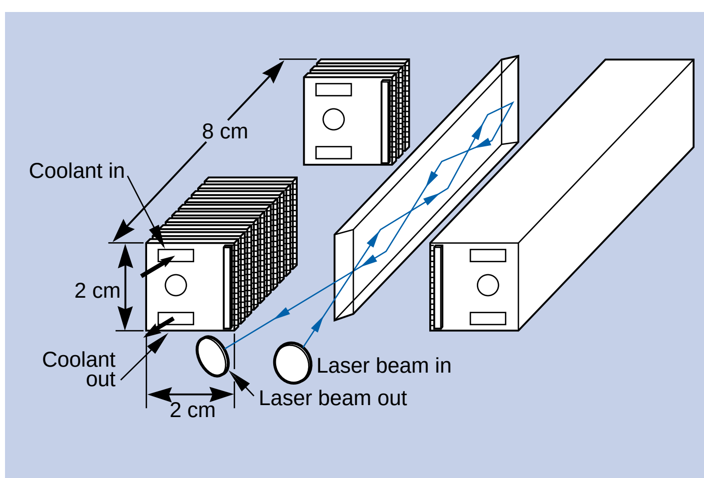


Figure 9. The layout of the diode pumps and the folded zig-zag lasing path for a full 82-diode-pump package.

it possible to develop high-power, diode-pumped, solid-state laser systems for a range of applications. For example, such lasers can be used, in materials fabrication, to weld and join materials with dissimilar thermal conductivity and melting points. The beam quality of these lasers would allow the welder to heat the smallest area possible next to the weld. With fiber-optic delivery, these lasers could even be used for welds in seemingly inaccessible places, greatly simplifying the assembly of a material.

Such lasers can also be used to machine very small holes through several millimeters of steel. For example, it has been discovered that perforating the leading edge and part of the upper section of an airfoil has very beneficial effects on aircraft performance—potential fuel savings of 20% have been quoted.[3] Typically, the laser machines 50-μm holes at a density of around 100 holes per square centimeter, for a total of a few hundred million holes. Even at the demonstrated kilohertz repetition rates, it will still take several (24-hour) days of continuous operation to perforate the fraction of the wing surfaces of a typical widebody aircraft.

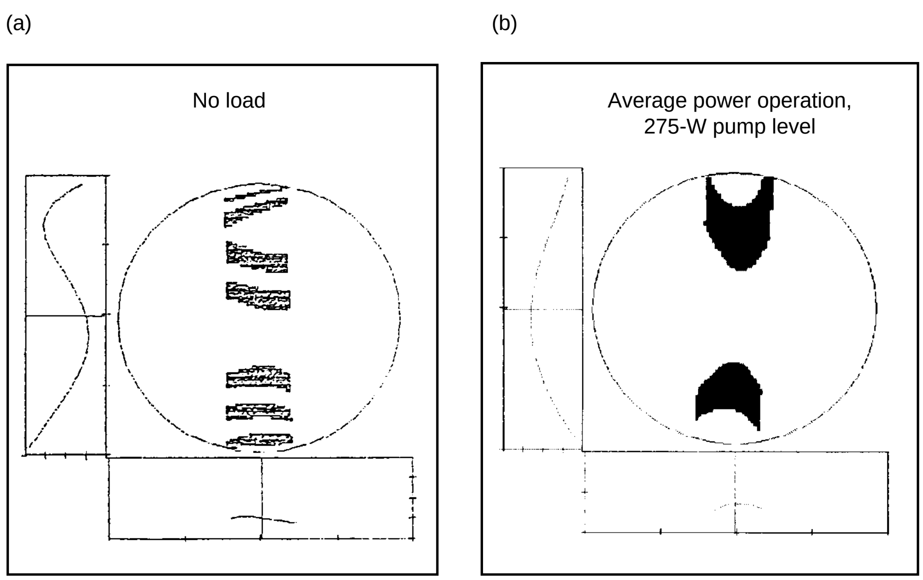


Figure 10. Mach-Zehnder interferogram of wave-front contours at 1.06 μm with the tilt removed for a slab that is (a) fully pumped and (b) unpumped.

Conclusion

The capability of cooling laser diode bars in an architecture that allows the construction of a high-irradiance pump source for solid-state lasers, together with a beam path that exploits the very beneficial average-power thermomechanical properties of crystalline solid-state laser materials, makes high-repetition-rate, diode-pumped slab lasers ideally suited for high-repetition-rate, small-single-pulse-energy, average-power applications. We have built a 1-kW version of this laser design to verify the basic concepts of high-average-power diode packaging and wave-front control in the new zig-zag architecture. With what we have learned in the process, it is quite straightforward to build versions that exceed 2 kW and have very-near-diffraction-limited beam quality. Such lasers will have numerous applications in the military as well as the civil sector.

Key Words: laser diode pumps; microchannel heat sinks—silicon etched; slab laser—diode-pumped, geometry, high-average-power, solid-state.

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" This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

U.S. Government Printing Office: 1998/683-051/60041

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