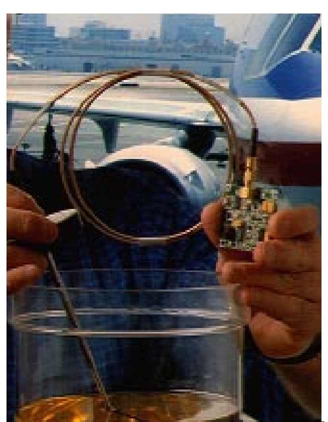
Livermore Wins Six R&D "Oscars"

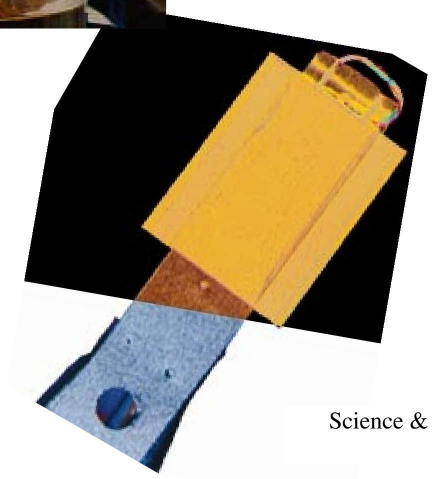
ON October 14 in Philadelphia, *R&D Magazine* will honor Livermore researchers with six of its annual R&D 100 Awards, considered the "Oscars" of applied research. Since 1978, when the Laboratory began to participate in the competition, technologies developed at Livermore have won 61 R&D 100 Awards.

All entries in the competition are judged by a team composed of *R&D Magazine* editors and other experts who look for the year's most technologically significant products and processes. Past winners have included the fax machine, Polacolor film, and the automated teller machine—products without which we can hardly imagine life today.

Two of this year's Laboratory winners stem from partnerships with American industry. Karena McKinley, acting director of the Laboratory's Industrial Partnerships and Commercialization office, says, "It is always a pleasure to see the industrial community recognize Laboratory work that has sprung from our basic mission activities. This recognition indicates that many of our newly developed technologies will make an impact on the American economy.

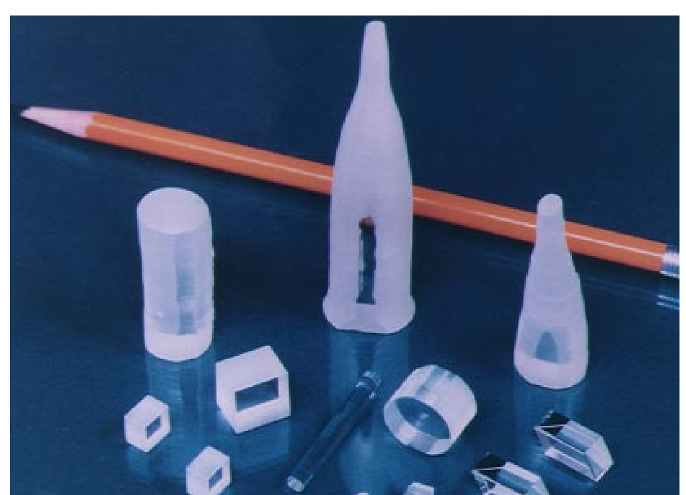
"We are proud of our Laser Programs Directorate, which this year produced five winners. We hope that the individual winners and the winning interdisciplinary teams will serve as models for other inventors. Exciting research relevant to industry is taking place all over the Laboratory, even though all six winners this year—including the one from the Physics Directorate involving an optical amplifier—have some connection to laser technology. Many other Livermore-developed technologies have similar potential."





The technologies that were honored have a range from everyday to very specialized uses:

- The latest micropower impulse radar (MIR) application is an electronic dipstick to sense the level of fluid or other material stored in tanks, vats, and silos. It can also be used in automobiles to read levels of a variety of fluids. The dipstick is impervious to condensation, corrosion, or grime on the sensor element, which is a simple metal strip of wire several inches to dozens of feet long, depending on the application. MIR works like conventional radar by sending out a pulse and measuring its return, but each microwave pulse is a few billionths of a second in duration.
- A tiny, semiconductor optical amplifier uses a miniature laser to boost data communications signals at ultrahigh (terabit-per-second) rates. It solves many of the problems that have plagued similar amplifiers: it is much smaller and cheaper than fiber amplifiers, which are used today to allow hundreds of thousands of telephone conversations on a single fiber-optic cable, and it is virtually free of crosstalk and noise at high transmission rates, unlike conventional semiconductor optical amplifiers. This amplifier will be useful in cable television distribution systems and other computer interconnections in fiber-to-the-home applications.



- A small, noncontact optical sensor will improve the manufacturing processes that employ robots by eliminating the time-consuming and expensive process of "teaching" robotic machinery new motions when manufacturing changes are required. This six-degrees-of-freedom (called SixDOF) sensor can sense its position relative to a piece being machined, allowing the robot to autonomously follow a pre-described machining or manufacturing path. As its name implies, the SixDOF sensor senses its position in all six degrees of freedom (the *x*, *y*, and *z* axes as well as the turning motion around those axes). Its nearest competitor can sense just three degrees of freedom.
- A new optical crystal (Ce:LiSAF) makes an all-solid-state, directly tunable, ultraviolet (UV) laser commercially viable for the first time. Developed jointly with VLOC Inc (a division of II-VI Inc) of Tarpon Springs, Florida, the crystal consists of lithium–strontium– aluminum–fluoride doped with cerium, a rare-earth metal. The crystal is a component of a compact solid-state laser that is practical, robust, and well suited to such remote sensing applications as detecting ozone and sulfur dioxide in the environment or detecting certain components of biological weapons. It could also be used for laser radar systems or for secure wireless communication links.
- The advanced magnetic sensor, a critical component in magnetic storage devices such as computer hard-disk drives, has been developed in conjunction with Read-Rite Corporation of Fremont, California. This new sensor offers greater sensitivity and 100 times greater storage densities than current commercial products. In fact, its storage density limit approaches the projected limit of magnetic disk drive technology of 100 gigabit/1 in^2 (6.4 cm^2). Using thin-film technologies previously developed at Livermore, the sensor is built of alternating layers of thin magnetic and nonmagnetic materials.
- The development of cost-effective, large-area, laser interference lithography is a way to precisely and uniformly produce regular arrays of extremely small (less than 100 atoms wide) electron-generating field-emission tips. It will significantly advance the effort to fabricate field-emission display (FED) flat panels. FED flat panels are a major improvement over active matrix liquid crystal display technology because they consume less power and can be made thinner, brighter, lighter, and larger, and with a wider field of view. Potential applications range from more efficient portable computers to virtual-reality headsets and wall-hugging TV sets.

These six Lawrence Livermore National Laboratory R&D 100 Awards and the inventors who made the new technologies possible are featured in the articles that follow.

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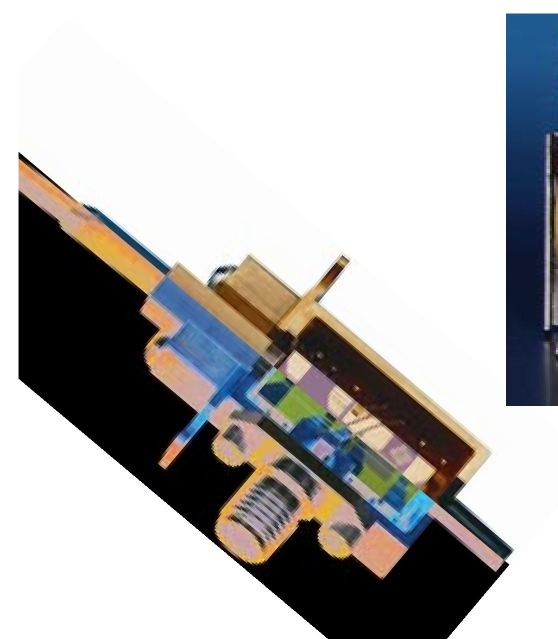
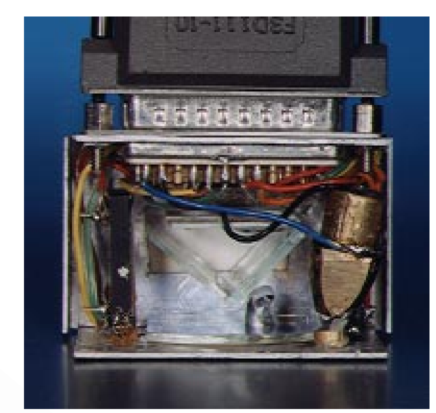
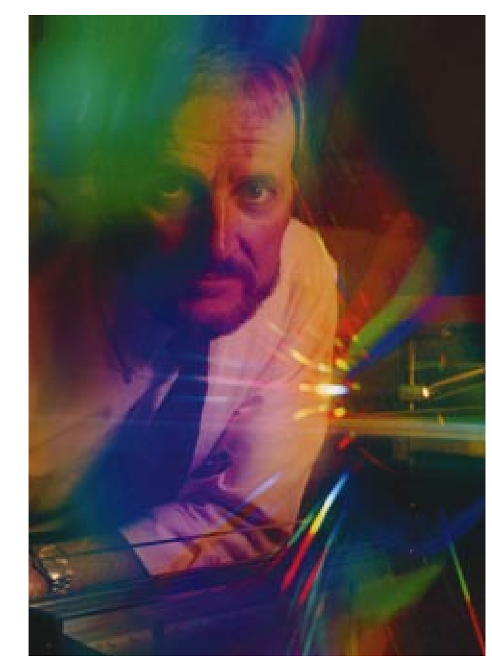


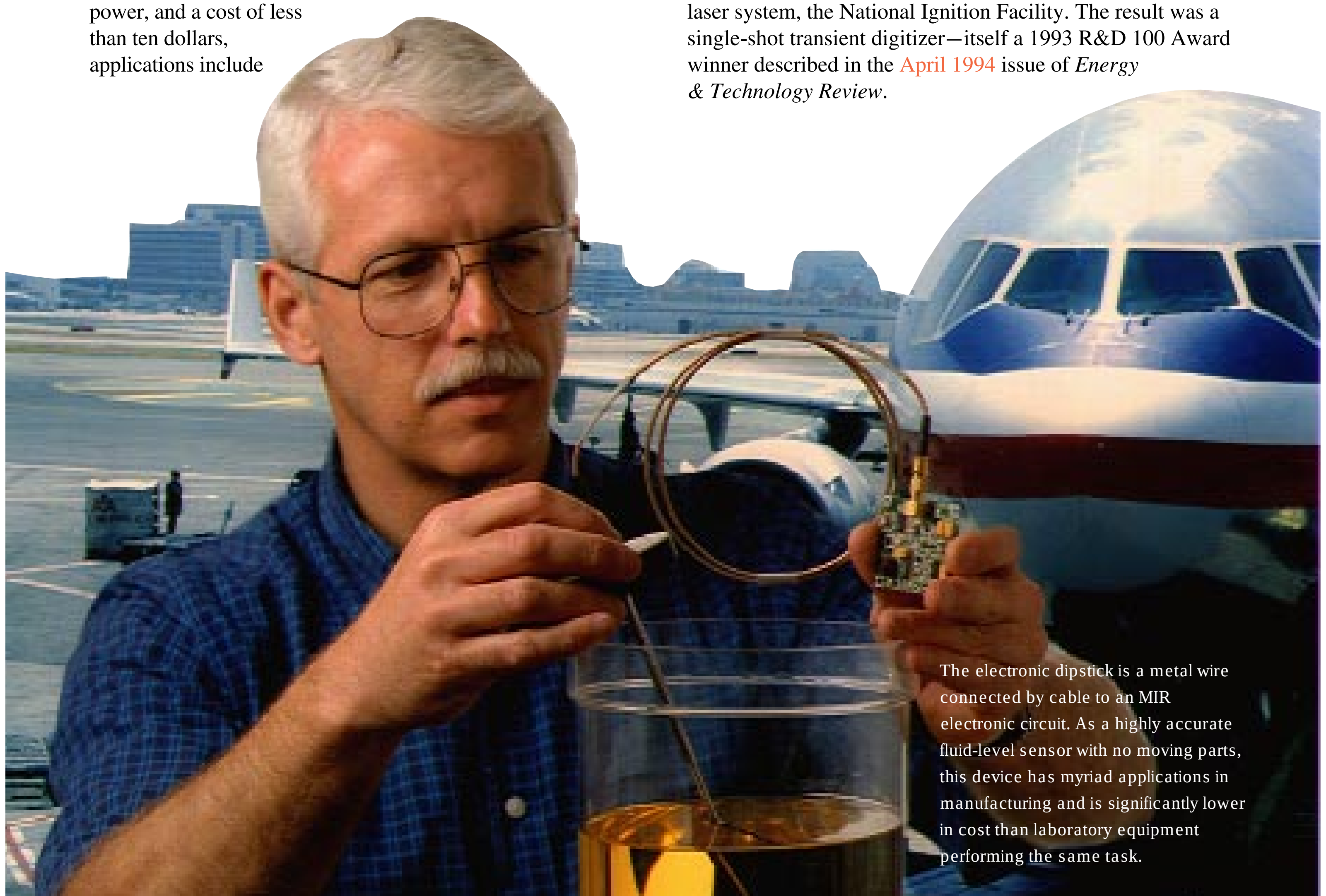




Electronic Dipstick Signals New Measuring Era

FANCY recalling for your grandchildren the flourishes you once made with the special (oily) rag and foil-like automobile dipstick, lunging (and cajoling) the dipstick into the narrow sleeve to measure the oil level before embarking on the family vacation. Already, a young face looks back at you with disbelief or rolled back eyes because that old dipstick and other fluid measuring devices were replaced way back in the mid-1990s with Tom McEwan's invention—the electronic dipstick.

One result of a string of spin-off technology developments in the Lawrence Livermore Laser Programs, the electronic dipstick is a device that measures the time it takes for an electrical impulse to reflect from the surface liquid in a container, so fluid level can be calculated. At better than 0.1% accuracy, extremely low power, and a cost of less than ten dollars, applications include measuring fluid levels in cars, oil levels in supertankers, and even corn in a grain elevator. Unlike ultrasound and infrared measurement devices, the electronic dipstick is not tripped up by foam or vapor, extreme temperature or pressure, or corrosive materials. Over time, the technology will make other fluid-level sensing devices obsolete.



The electronic dipstick is a metal wire connected by cable to an MIR electronic circuit. As a highly accurate fluid-level sensor with no moving parts, this device has myriad applications in manufacturing and is significantly lower in cost than laboratory equipment performing the same task.

Spin-Offs from Digitizing to Measuring

Lawrence Livermore is home to the 100-trillion-watt Nova laser. Developed for nuclear fusion research, the ten-beam pulsed Nova laser generates subnanosecond events that must be accurately recorded. In the late 1980s, Laboratory engineers began to develop a new high-speed data acquisition system to capture the data generated by Nova and the next-generation laser system, the National Ignition Facility. The result was a single-shot transient digitizer—itself a 1993 R&D 100 Award winner described in the April 1994 issue of *Energy & Technology Review*.

The LLNL transient digitizer, which is the world's fastest, functions as a high-speed oscilloscope combined with a digital-readout device. The instrument records many samples from single electrical events (a brief signal called a "transient"), each lasting only 5 nanoseconds (5 billionths of a second). Compared to competitive products, such as the best oscilloscopes, the transient digitizer is much smaller and more robust, consumes less power, and costs far less.

While developing the transient digitizer, project engineer McEwan had an important insight. The sampling circuits developed for it could form the basis of a sensitive receiver for an extremely small, low-power radar system. What ensued was the development of micropower impulse radar (MIR). (For more MIR information, see January–February 1996 *Science & Technology Review*.)

The principal MIR components are a transmitter with a pulse generator, a receiver with a pulse detector, timing circuitry, a signal processor, and antennas. The MIR transmitter emits rapid, wideband radar pulses at a nominal rate of 2 million per second. This rate is randomized intentionally to create a distinctive pattern at a single location, which enables the system to recognize its own echo, even with other radars nearby. The components making up the transmitter can send out shortened and sharpened electrical pulses with rise times as short as 50 trillionths of a second (50 picoseconds). The receiver, which uses a pulse-detector circuit, only accepts echoes from objects within a preset distance (round-trip delay time)—from a few centimeters to many tens of meters.

The MIR antenna determines many of the device's operating characteristics. A single-wire monopole antenna only 4 centimeters long is used for standard MIR motion sensors, but larger antenna systems can provide a longer range, greater directionality, and better penetration of some materials such as water, ice, and mud. Currently, the maximum range in air for these low-power devices is about 50 meters. With an omnidirectional antenna, MIR can look for echoes in an invisible radar bubble of adjustable radius surrounding the unit. Directional antennas can aim pulses in a specific direction and add gain to the signals. The transmitter and receiver antennas, for example, may also be separated by an electronic "trip-line" so that targets or intruders crossing the line will trigger a warning. Other geometries, with multiple sensors and overlapping regions of coverage, are also being explored.

The first application McEwan dreamed possible was a burglar alarm, but other popular spin-offs of the MIR technology have been the electronic dipstick, auto safety devices such as an anticrash trigger, a heart monitor that measures muscle contractions instead of electrical impulses, mine-detecting sensors for the military, and corrosion detectors for rebar buried within concrete bridges. Within the next few years, the MIR technology may well become one of the top royalty revenue-generating licenses connected with any U.S. university or national laboratory. So far, over a dozen companies have entered into license agreements with the MIR technology, generating nearly $2 million in licensing agreements with the Laboratory, and soon royalties will add to that amount. To date, most of these licenses (9 of 15) are for the electronic dipstick.

How the Electronic Dipstick Works

The electronic dipstick uses the MIR fast-pulse technology to launch a signal—from a launch plate rather than an antenna—along a single metal wire rather than through air and measures the transit time of reflected electromagnetic pulses from the top of the dipstick down to a liquid surface. The air–liquid boundary is the discontinuity that reflects the pulse; the time difference between a pulse reflection at the top of the dipstick and a reflection at the air–liquid boundary indicates the distance along the line. The liquid level is thus measured from the top of the tank (the dielectric is air, which for all practical purposes does not vary with temperature or vapor content). The transmission line for the dipstick may be configured as microstrip, coaxial cable, or twin lead, whichever suits the application.

The strength of the pulse reflected from the air–liquid boundary and from the subsurface liquid–liquid boundary can be measured. When the liquid has a low relative dielectric constant, such as JP-3 jet fuel, only a portion of the pulse is reflected at the air–liquid boundary, and the remaining portion continues into the liquid until another discontinuity is reached, such as an oil–water boundary or the tank bottom itself. Thus, the dipstick can also provide additional information about conditions within the tank. The photo on p. 16 shows the entire dipstick assembly with its simple digital output display, although the output could be connected directly to an analog meter. The dipstick's 14-bit, high-resolution output provides continuous readout that is accurate to within 0.1% of the wire's maximum length, and it functions at temperatures from –55 to 85°C (–67 to 185°F). Already, companies have shipped products that use this technology of the future.

Key Words: electronic dipstick, micropower impulse radar (MIR), R&D 100 Award, transient digitizer.

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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.

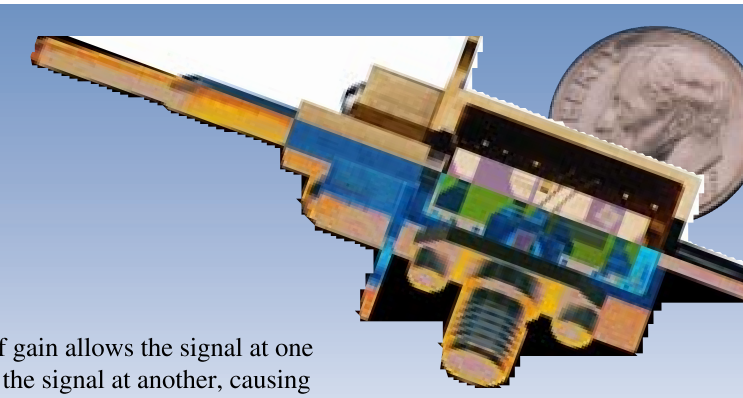
Fiber amplifiers can operate at comparable bit rates, but they are large and expensive, which limits their usefulness. For example, erbium-doped fiber amplifiers currently enable hundreds of thousands of simultaneous telephone conversations across continents and under oceans on a single fiber-optic cable. 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 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.

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

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.

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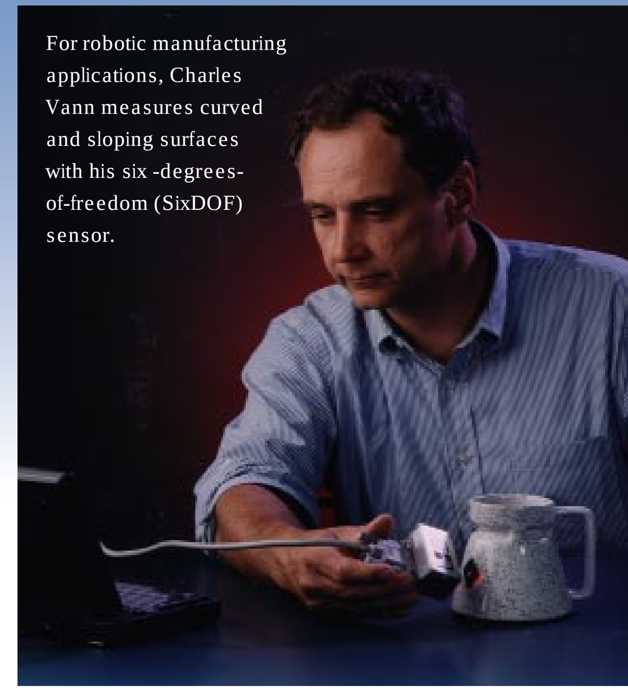
SixDOF Sensor Improves Manufacturing Flexibility

MODERN manufacturing makes heavy use of robots, which are better than humans at repeating the same task over and over. But when even minor changes need to be made in the manufacturing process—in the shape of a car door, for example—a human operator must “teach” the robot the new shape by guiding it by hand through each motion and every orientation in the operation. Besides being time consuming and therefore expensive, this process is often inaccurate.

Charles Vann, a Lawrence Livermore National Laboratory mechanical engineer and manager, has developed a sensor that can make manufacturing robots smarter, saving both time and money. His small, noncontact, optical sensor increases the capability and flexibility of computer-controlled machines by detecting the sensor’s relative position to any mechanical part in all six degrees of freedom. (In mechanics, degrees of freedom refer to any of the independent ways that a body or system can undergo motion, i.e., straight-line motion in any one of the three orthogonal directions of space or a rotation around any of those lines.) The six-degrees-of-freedom (SixDOF) sensor can be mounted on the tool head of a multi-axis robot manipulator to track reflective reference points attached to the part. Once the robot knows where it is relative to the part, a computer can instruct the robot to follow a path predescribed in multidimensional computer drawings of the part, or the robot can be programmed to follow a path of references mounted on the part. The sensor eliminates the need for “training” the robot and enables process changes without halting production because software can be downloaded quickly into the robot’s controller.

The nearest competitor to the SixDOF sensor is one that detects only three degrees of freedom. But many manufacturing operations require information on all six degrees of freedom. Welding, for example, requires information on three degrees of freedom to locate the weld (the *x*, *y*, and *z* axes) and the other three rotational degrees of freedom to properly orient the tool relative to the part. Compared to the competitor, the new SixDOF sensor is four times smaller and five times lighter because it uses lateral-



For robotic manufacturing applications, Charles Vann measures curved and sloping surfaces with his six-degrees-of-freedom (SixDOF) sensor.

effect photo diodes (light- and position-sensitive diodes), which are smaller and lighter than the cameras used by the competition. And the SixDOF sensor costs one-sixth as much. Yet for an equivalent field of view, it is more than 250 times faster and up to 25 times more accurate.

How the Sensor Works

The SixDOF sensor is composed of four assemblies: a laser illuminator, beam splitting and directing optics, lateral-effect photo diodes, and signal-processing electronics. The laser source is a 5-milliwatt diode laser. Two small mirrors (M1 and M2 on the illustration, next page) guide the 1-millimeter laser beam to the primary optical axis of the sensor. The beam then passes through two negative lenses (L1 and L2) that diverge the beam at about 0.3 radians. This high divergence creates a 2-centimeter laser spot at about 3.5 cm from the face of the sensor. The beam divergence, depth of field, and spot size can be changed by choosing different negative lenses.

Two reflective reference points, a 4-millimeter dot and a 1-by-1-mm bar, are mounted on nonreflective tape and applied to the part being worked on. The laser light reflects off the references and back into the sensor. Because the beam is diverging, the reflections are magnified in area when the light returns to the sensor, allowing most of the light to go around the negative lenses and through a large, collimating lens (L3) instead. After collimation, the beam continues through a notch filter, which passes the laser light but blocks light at other wavelengths.

Inside the sensor, light from the dot is divided into two beams by a beam splitter. Half of the beam is reflected

90 degrees into photo diode P3. The other half of the beam passes through the beam splitter, into a focusing lens L3, and onto photo diode P2.

The light from the second reflective surface, the bar, also passes through the filter. However, because this reflective bar is tilted relative to the dot, the laser light reflecting from it is at a greater angle of divergence. The greater angle causes the light to pass through a different location of the filter, missing the collimating lens and illuminating another photo diode (P1).

Through creative use of mirrors and lenses, each of the three photo diodes has a different sensitivity to the relative position of the sensor and the reflectors. P1 is most sensitive to straight-line motion between the bar and the sensor *z* and the rotation of the sensor about that axis (R*z*). P2 is most sensitive to tilt about the *x* and *y* axes (R*x* and R*y*), and P3 is most sensitive to straight-line motion of the sensor relative to the reference dot (*x* and *y*). Information from all three sensors is needed to determine all three positions and three orientations of the sensor relative to the part.

The signals from the three photo diodes are processed by electronics remotely located from the sensor head. The analog data from the diodes are digitized and fed into a computer where they are decoupled to define the six axes of information. The processed data are then available to the operator for recording or sending commands to change the position of a computer-controlled machine.

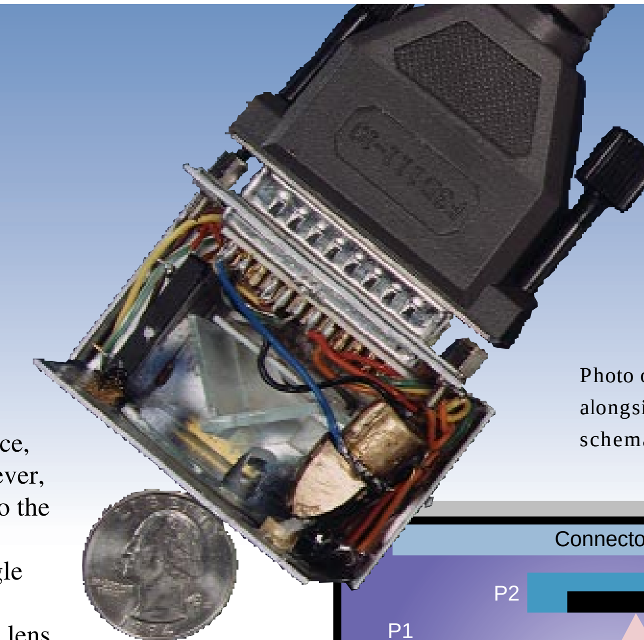
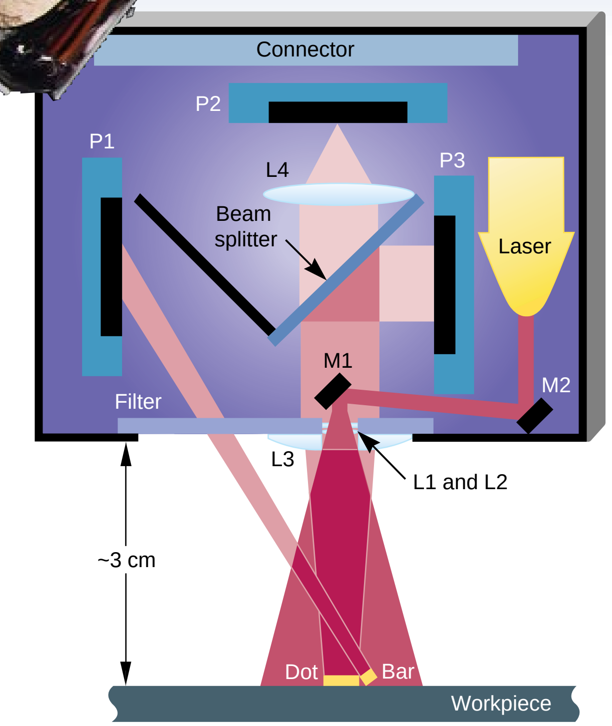


Photo of sensor with a quarter lying alongside. Below is an interior schematic view of sensor.



A Better Mouse

Among other future uses for Vann’s new sensor is a SixDOF cursor for personal computers, which would allow a user to perform much more complicated tasks than are possible today with a typical two degrees-of-freedom mouse. The sensor could also be used to help doctors diagnose muscle recovery by evaluating the effects of physical therapy. With reflective reference points mounted on a patient’s injured limb, a robot with a SixDOF sensor could generate a SixDOF map of muscle motions. The sensor could also remotely perform dangerous tasks such as manipulating radioactive, toxic, or explosive materials. For example, a robot with a SixDOF sensor could track reflective references mounted on the hands of an operator who disassembles a dummy bomb while another robot, electronically following the motions of the first robot, disassembles the real one.

Its potential applications are diverse, but the SixDOF sensor will likely find its greatest use in manufacturing where highly agile and accurate machines have been limited by their inability to adjust to changes in their tasks. Enabled to sense all six degrees of freedom, these machines will be able to adapt to new and complicated tasks without human intervention or delay.

Key Words: manufacturing, robotics, R&D 100 Award, six-degrees-of-freedom (SixDOF) sensor.

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A Simple, Reliable, Ultraviolet Laser: the Ce:LiSAF

The Livermore team that developed the ultraviolet Ce:LiSAF laser includes (front, from left) Stephen Payne and Christopher Marshall; (back, from left) Andy Bayramian, John Tassano, Joel Speth, and William Krupke.

Go through a supermarket checkstand and, chances are, your purchases will be scanned by a laser. Watch TV and see advertisements for excimer laser surgery to correct nearsightedness. The list goes on, for laser technology has infiltrated modern life. But this hardly means that laser research and development is complete. Now, Lawrence Livermore National Laboratory laser scientists are engaged in two directions of research: advancing to more and more difficult applications, and refining current technology so that lasers can be made ever more efficient, reliable, and cost effective. For consumers, the progress of this work will be marked by seeing previously exotic applications become commercially feasible.

The move toward smaller but more powerful, more reliable, and less expensive lasers has taken a jump with the discovery of Ce:LiSAF, a laser crystal developed under the terms of a Cooperative Research and Development Agreement (CRADA) between the Laboratory and VLOC, a Division of II-VI Inc (formerly Lightning Optical Corporation) in Tarpon Springs, Florida. Ce:LiSAF is the nomenclature for a crystal made of cerium embedded, or doped, in a host medium consisting of lithium strontium aluminum fluoride ($LiSrAlF_6$). It is an optical crystal, emitting ultraviolet light in a range of wavelengths that make the laser tunable.

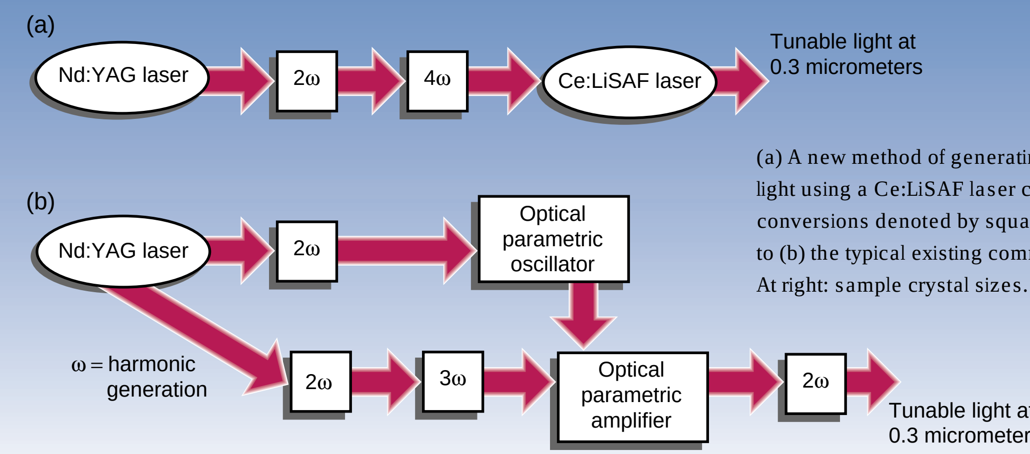
The new cerium laser crystal is a significant product for two reasons. First, it provides the ability to generate ultraviolet light directly, compared to previous methods that were far more complicated, less predictable, and worked only under restrictive conditions. Ultraviolet light is desirable for applications that require finely focused, high-intensity beams or for sensing materials with ultraviolet absorption bands. Of the various kinds of laser light—infrared, visible, and ultraviolet—ultraviolet is the most difficult to obtain because it consists of the highest energy wavelengths. The capability of generating ultraviolet light simply and directly will extend laser applications.

The older, usual method for generating tunable (variable color) ultraviolet laser light is to take available, longer wavelengths and use various means to step them up through intermediate wavelengths until the ultraviolet portion of the energy spectrum is reached. This delicate process is called frequency conversion. The figure at right compares the frequency conversion required for the new laser crystal with an existing commercial approach for generating ultraviolet light. In the laser using the Ce:LiSAF crystal, input energy from a Nd:YAG (neodymium-doped yttrium aluminum garnet—a commonly used crystal) laser undergoes nonlinear frequency conversion twice. That light is beamed through the Ce:LiSAF crystal, and ultraviolet light is the result. In the existing commercial approach, one beam pumped through a Nd:YAG crystal undergoes frequency conversion; the resulting light is used as input energy for a nonlinear optical parametric oscillator. A second beam from the Nd:YAG crystal goes through two frequency conversions, is combined with the output from the oscillator, and is mixed in an optical parametric amplifier. The resulting light must then go through frequency conversion before ultraviolet light is attained. With two fewer critical frequency conversion steps, the Ce:LiSAF-based method results in more reliable and efficient generation of ultraviolet light, with less energy lost along the way.

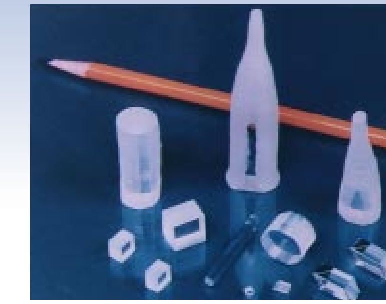
The second reason why the new crystal is significant is that it makes an ultraviolet solid-state laser system commercially feasible. Generating laser light is not simple because much of the energy put into the laser system ends up as heat. Yet light energy gain must be larger than the losses if lasing is to occur. Therefore, in every part of the laser system, the objective is to maximize energy gains while minimizing the losses. The cerium laser crystal, which was specifically designed to be an amplifying agent in a solid-state system, generates useful ultraviolet wavelengths so simply that it makes possible a compact, robust, and cost-effective laser system.

Crystal Properties

In the Ce:LiSAF crystal, cerium is the light emitter while lithium strontium aluminum fluoride serves as the crystalline host and preserves the favorable optical properties of cerium.



(a) A new method of generating tunable ultraviolet light using a Ce:LiSAF laser crystal (nonlinear conversions denoted by square boxes) is compared to (b) the typical existing commercial approach. At right: sample crystal sizes.



The atomic structure of cerium provides the property of transitioning to the ultraviolet wavelengths when it is bombarded with light. This is an advantageous property, and scientists have been investigating cerium's potential as an ultraviolet laser since the early 1980s. However, early demonstrations were so discouraging that cerium was all but dropped from active experimentation and commercial consideration. What was happening was that cerium-doped crystals had developed two major energy-loss problems: solarization and excited-state absorption. Solarization is the loss of transparency in a crystal—it becomes colored—from ultraviolet radiation, like sunlight. Excited-state absorption causes input energy to turn into heat instead of laser light, which also can be debilitating to the laser.

To make use of cerium's ultraviolet properties, a complementary host medium was needed to provide it with stability against ultraviolet radiation and the effects of excited-state absorption. Over the years, Laboratory scientists investigated different host media and built up a body of data about them. In the mid-1980s, Stephen Payne and co-workers invented the LiSAF laser host medium for use with chromium-doped infrared lasers. This very successful material, used in commercial laser designs, was selected for trials with cerium.

CRADA Partnering

For the experiments, making the crystals was an important, but difficult and time-consuming first step. Much can go wrong during the process, resulting in damaged, contaminated, or flawed pieces with the wrong optical characteristics. Fortunately, the Laboratory scientists had an opportunity to enter into a CRADA with the scientists at VLOC, who had expertise in growing crystals and manufacturing them with high yield. In addition, VLOC provided a range of facilities for precision crystal cutting and polishing and a means for purifying chemicals for the crystal growth process. The closeness of the Laboratory–VLOC collaboration, in which laser-crystal analysis and fabrication cycles were carefully coordinated, eventually led to the successful production of the cerium laser crystal on a routine basis.

The new cerium laser offers efficiencies approaching 50%, which means that extracted laser light is about half of the energy that was input into the laser. This value is in the range of efficiencies for commercial laser products at nonultraviolet wavelengths. Furthermore, this material is from 10 to 100 times more efficient than other types of solid-state laser material that have been studied in the past. Finally, because the ultraviolet light is provided in a wavelength range corresponding to approximately 10% of the bandwidth, the ability to tune, or shift, to another wavelength for particular applications is an additional critical feature that this laser provides.

Applications

Because it is straightforward technology, Ce:LiSAF is expected to usher in a new era of laser applications. It is particularly well suited to remote sensing environmental applications because many targeted molecules, including ozone and aromatic compounds, have characteristic absorption bands in the ultraviolet. Already, a cerium laser has been deployed to remotely detect ozone and sulfur dioxide in the environment.

The U.S. Army is considering its use to monitor the presence of tryptophan, a common component of biological weapons. Another potential military use could be to secure wireless communications links between infantry units over short distances of approximately 1 kilometer on a battlefield. Because ultraviolet light from a cerium laser can be tuned to attenuate, or taper off, around 1 kilometer from the source, it can be detected only by receivers within less than about 10 kilometers of the transmitter. This feature makes remote detection of the communication signals (for example, with a satellite or behind enemy lines) impossible.

The power, simplicity, and reproducibility of Ce:LiSAF will change traditionally difficult, expensive, and sensitive applications into commercially feasible ones. Because of this crystal, tunable ultraviolet lasers may move rapidly from the domain of scientific research laboratories into industry.

Key Words: Ce:LiSAF, cerium crystal, R&D 100 Award, tunable ultraviolet laser, solid-state laser.

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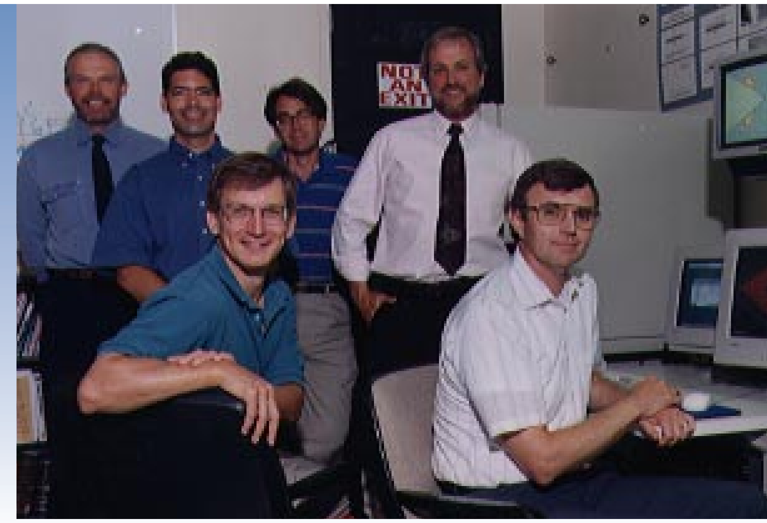
Giant Results from Smaller, Ultrahigh-Density Sensor



Livermore team members include (clockwise from top, left) Stephen Vernon, James Spallas, Charles Cerjan, Nat Ceglio, Andrew Hawryluk, and Don Kania. (Not pictured are Benjamin Law and Daniel Stearns.)

"MORE, faster, smaller, and cheaper" is an underlying theme of the computer industry. Ironically, one recent technical development that is contributing to this pace came from a group of Lawrence Livermore scientists who were headed toward quite different scientific objectives. But their scientific expertise coupled with some creative thinking led Daniel Stearns and his colleagues in the Advanced Microtechnology Program of the Laser Programs directorate to develop a laser-based spin-off for computer industry use. They designed an advanced, ultrahigh-density magnetic sensor that will solve a problem facing the disk drive industry: how to get beyond the density and storage limitations of present magnetic sensor technology.

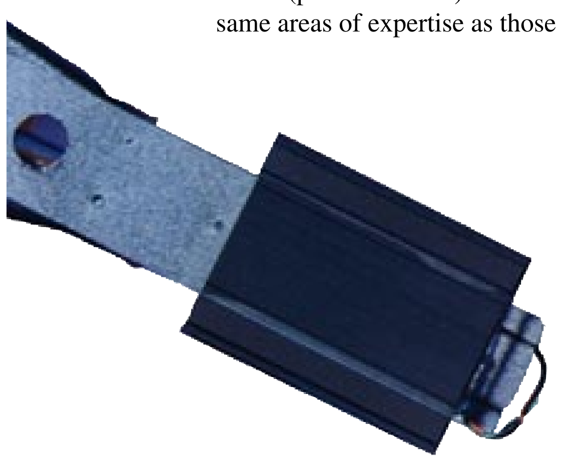
Magnetic sensors are a key component of the disk drive. They determine how much and how fast the disk drive can "read." Because computer users are constantly demanding higher density disk drives (with more memory in the same physical space), manufacturers must constantly push to make smaller and smaller magnetic sensors. Unfortunately, practical size limits have been reached with present sensor technology. As sensors are made smaller, their performance degrades. The performance limits have to do with signal-to-noise ratio: smaller sensors give off smaller signals. At some point, the signals become too small to distinguish from the "noise" coming from the rest of the sensor environment.

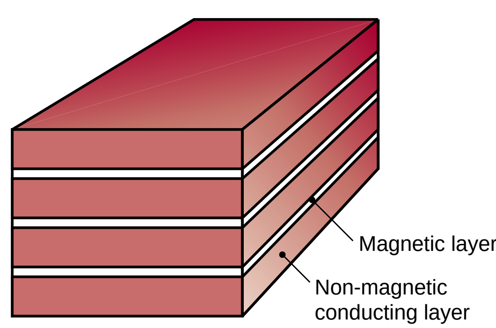
The team (pictured above) was working in some of the same areas of expertise as those in magnetic sensor research and development, and they became intrigued by the solutions that industry researchers were proposing for the magnetic sensor problem. They wondered what they might be able to do to help solve it.

Industry researchers were investigating magnetoresistive and giant magnetoresistive (GMR) devices. Magnetoresistance—the change in a conducting material's resistivity when a magnetic field is applied to it—was also recognized by the Livermore team as a promising tool for sensing very small volumes of magnetic media. As they began thinking about the problem, they looked at the GMR devices already developed. They applied their expertise about thin, multilayer films, magnetics, and microfabrication technologies and emerged with a variation on the most promising GMR concept at the time, the "spin-valve" GMR sensor. They called their sensor the CPP–GMR sensor (CPP stands for current perpendicular to the plane).

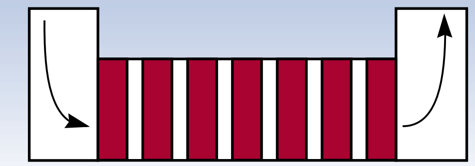
Simply Different Structures

The CPP–GMR sensor is a microstructure made up of alternating ferromagnetic layers and nonmagnetic metal layers, or spacers. The layers are thin, generally less than 5 nanometers each, and each sensor may contain a total of 10 to 100 individual layers (depending upon material choices and applications). The layer thicknesses are selected to maximize the GMR effect. The total thickness of the sensor is often only approximately 100 nanometers thick, about one-thousandth the width of a human hair.





The CPP-GMR sensor uses alternating thin film layers of magnetic and nonmagnetic materials and shape anisotropy that is inherently stable along the long axis.



Configuration of the CPP–GMR sensor.

The width and length of the sensor are small enough to allow the individual ferromagnetic layers to form as single magnetic domains with a preferred magnetic orientation. These orientations are deliberately designed to be antiparallel to each other. Typically, the width of the sensor is 100 to 500 nanometers, and the length is 250 to 1,000 nanometers—a tiny shoe box shape (see photo and figure below left).

In the absence of an external magnetic field, the sensor relaxes to its lowest energy state, with the alternating ferromagnetic layers aligning in an antiparallel configuration. Sensor resistivity is higher in this state because current that flows perpendicularly through the multilayer planes encounters greater electron scattering, which increases the resistivity. When a sufficiently large magnetic field is applied to the sensor, the ferromagnetic layers rotate into a parallel magnetization state. In this configuration, current flowing through the multilayer planes encounters reduced electron scattering and as a result, resistivity is lower. The two resistivity states can be used as the two states in a digital magnetic sensor.

The performance of the CPP–GMR sensor is a significant improvement over conventional GMR sensor design. Stearns' design has the GMR multilayers rotated 90 degrees so that the current flows perpendicular to the plane of the sensor (see figure above). Because the signal from the CPP–GMR sensor is inversely proportional to its cross-sectional area, the signal actually increases as the sensor is scaled to higher and higher densities (and smaller sensor size). This scaling provides great manufacturing cost advantages for the future.

There are additional advantages to the CPP–GMR architecture. Conventional GMR sensors require shielding to be placed around the sensor for protection from stray flux, and the shields must be electrically isolated from the sensor. The extra parts and related design effort affect sensor size and cost.

On the other hand, the Laboratory's CPP–GMR sensor is well integrated into the design of the magnetic head: it uses the "write" poles of the magnetic head to serve as shields for the sensor and as conductors for the magnetoresistive current. As a result, the sensor conductors, the shields, and the inductive write poles are all integrated into a single structure to simplify the design, manufacture, and cost of the magnetic head.

Industrial Collaboration

After hearing about the potential for the CPP–GMR sensor, Read-Rite Corporation of Fremont, California, one of the world's leading supplier of magnetic heads, became an industrial collaborator with the Laboratory and has been working closely with the team to bring the product to market. The first results of this collaborative work included modifying the design to produce a linear sensor response, a conventional practice in commercial manufacturing, and devising a self-aligning process for multilayer manufacturing, which will greatly drive down manufacturing complexity and costs. Together the two groups are currently developing fabrication sequences and designing tools to use in manufacturing the sensor.

The CPP–GMR sensor will be able to function over a range of information storage densities, spanning from the current state-of-the-art at approximately 1 gigabit/in.^{2} (1 gigabit/6.4 cm^2) which is at the size limits of magnetic disk drive technology. To scale up to the sensor's upper density limits requires no change in the magnetic head architecture. The CPP-GMR sensor will be more robust and more sensitive as it is scaled down in size.

One interesting potential application for the sensor is the "patient ident-a-card," which would be credit-card size and contain the entire medical history of an individual. Another application could be storage on a single PC the equivalent information of the Library of Congress. The primary importance of the sensor, however, is that it contributes to continued growth in the computer industry. With higher-density sensors and heads, the industry will be able to continue developing products with greater performance at reduced cost.

Key Words: CPP–GMR (current perpendicular to the plane–giant magnetoresistive) device, disk drive, R&D 100 Award, ultrahigh-density magnetic sensor.

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Thinner Is Better with Laser Interference Lithography

FROM digital watches to portable computers, flat-panel displays form an integral part of a myriad of consumer and military products. The $8-billion annual worldwide market for flat-panel display technology, now overwhelmingly dominated by active matrix liquid crystal displays (AMLCDs), is projected to grow to more than $20 billion by the end of the decade.

However, as anyone using a portable computer can attest, liquid crystal displays have significant limitations in brightness, angle of viewability, and power consumption. For U.S. security and economic experts, an even more significant factor is the fact that liquid crystal display technology is dominated by Japanese companies; American firms control less than 3% of the market. A breakthrough for display manufacturing by Lawrence Livermore researchers, however, may well put U.S. flat-panel producers in a position to lead the market with a simple, cost-effective way to produce field-emission displays (FEDs).

Consuming less power than AMLCDs, FEDs are a new kind of flat-panel display technology that can be thinner, brighter, larger, and lighter. They have numerous potential applications in portable and large area displays and can, in principle, cost much less to manufacture.

Moving to FEDs

Active matrix technology uses liquid crystals sealed between two thin plates of glass, with the display divided into thousands of individual pixels that can be charged to transmit or block light from an external source to form characters or images on a screen. In contrast, each pixel in an FED acts as a microscopic cathode ray tube (CRT) and produces its own light. Instead of a single electron beam sweeping across an array of phosphor pixels as in a conventional CRT, the FED has millions of individual CRT-accelerated electrons crossing a vacuum gap and impinging upon a phosphor-coated screen to emit light.

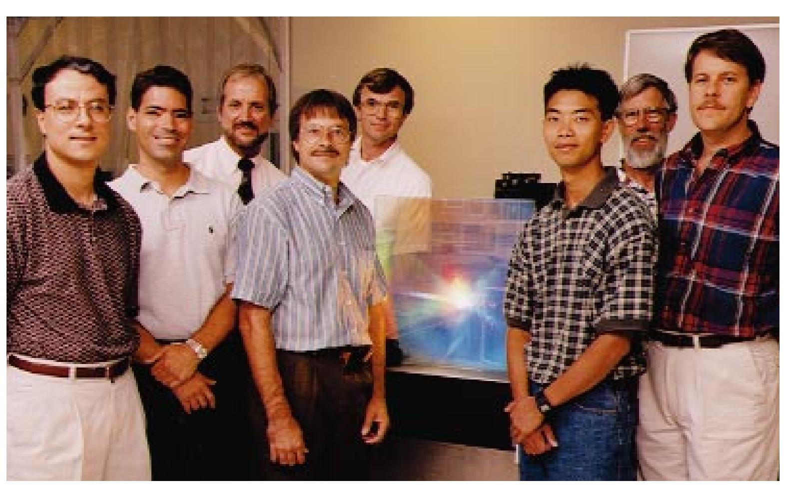
Switching on blocks of emitters that comprise a pixel in a given sequence achieves the same effect as changing a selected pixel in a liquid crystal display. What's more, FEDs produce high brightness over the full range of color, but could require only one-tenth to one-half the power of a conventional liquid crystal display.

The main problem with FEDs has been that their fabrication requires a micromachining technology with the ability to pattern very small structures over large areas. The display's electron-generating field emitter tips are less than 100 atoms wide and must be made precisely and uniformly over the entire screen area. Now, only small-scale (1 sq. in.) FEDs can be produced by the extremely slow and expensive process of electron-beam lithography. Conventional photo-lithographic techniques, while capable of producing larger arrays (approximately 10 sq. in.) cannot produce sufficiently small emitters.

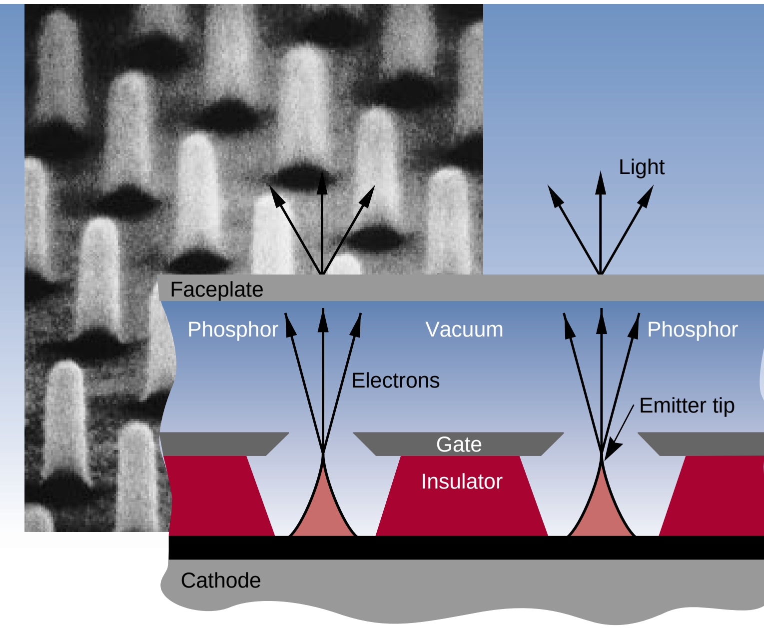
Citing U.S. firms' mediocre penetration into the critical flat-panel display market, the federal government formed the U.S. Display Consortium and assembled a White House Flat Panel Display Task Force. Both the consortium and the task force concluded that to develop a viable domestic flat-panel display industry, U.S. firms could either partner with an established Japanese manufacturer or "leapfrog" the technology with a new approach.

Leapfrogging the Competition

A leapfrog approach was demonstrated by a Lawrence Livermore team headed by Laser Programs physicist Michael Perry. The team perfected the process, called laser interference lithography, and they demonstrated its applicability to large (>2500 cm^2) patterning. The process is expected to aid substantially in the successful commercialization of high-performance FEDs and enable the technology to capture a significant share of the flat-panel market.



Developing this new flat-panel display technology are Andres Fernandez, James Spallas, Nat Ceglio, Jerald Britten, Andrew Hawryluk, Hoang Nguyen, Robert Boyd, and Michael Perry.



Large-format field-emitter mask pattern produced by laser interference lithography and the field-emission display (FED) concept.

Interference lithography has been used in a variety of other applications for more than 15 years, especially for fabricating diffraction gratings.* The technology offers the promise of low-cost, high-resolution, bright, and energy-efficient displays that are ideal for applications ranging from portable computers and instruments to virtual-reality headsets and large workstations. What's more, the technology may have direct applications to lower manufacturing costs of other products, such as computer memory chips.

The LLNL process can easily produce a high-density array of posts or holes 0.2 to 0.5 micrometers wide in a photosensitive material, perfect for creating densely packed and precisely arrayed patterns required for FED production. The technology allows the use of inexpensive substrates such as silicon and glass and works with proven photoresist materials and processes that are used in traditional lithography techniques.

Using Lasers to Produce Precise Patterns

The laser interference technique is based on the pattern produced by two interfering laser beams of a given wavelength. The standing wave interference pattern produces alternating light and dark fringes with a spacing determined by the angle at which the beams intersect. For a typical near-ultraviolet or violet laser operating in the range 0.3 to 0.4 micrometers, lines down to 0.2 micrometers can be fabricated, a resolution easily exceeding that required for FED manufacturing. With multiple exposures, essentially any pattern that can be formed by intersecting lines can be fabricated.

In order to apply interference lithography to array areas larger than 6,000-cm^2 (1,000-in.^{2}), the LLNL researchers further developed specialized techniques. For example, meniscus coating allows the substrate (such as silicon or glass) to be coated with the liquid photoresist solution to exactly the desired thickness.

Another technique that the team developed indicates when the pattern geometry is optimized. The growth of the features is monitored in real time during the development step. This process is critical because although the Livermore technology is relatively straightforward, many variables such as laser intensity, coating thickness, and temperature come into play simultaneously.

With the integration of these new fabrication procedures, the team has succeeded in fabricating 2,500-cm^2 (400-in.^{2}) arrays of submicrometer photoresist material suitable for the production of field emitters. The large arrays contain about 1 trillion submicrometer structures, with better than ±5% spacing uniformity.

Impressive Results Attracting Industry

The technical results have been so impressive that several major U.S. display producers and lithography vendors are collaborating with the LLNL development team. Some of these firms have successfully converted the pattern left by the photoresist material into functioning emitters by a series of etching and evaporation steps.

Team members say the new technique will find direct use in other applications requiring deep submicrometer patterns. The most significant may be a new method for the critical lithography steps in DRAM (dynamic-random-access-memory) chip manufacture, a $150-billion-per-year market. LLNL researchers are currently discussing the approach with major U.S. manufacturers to evaluate the DRAM application.

The first commercial products with FEDs manufactured with the Lawrence Livermore process may be high-resolution units for military needs such as in aircraft and ground vehicles. Somewhat later, FEDs should start appearing in such consumer products as portable and desktop computers and even flat-screen televisions with picture quality comparable to that from the best conventional cathode ray tube TV displays.

The laser interference lithography process is part of a much larger effort involving a dozen industrial collaborations working to advance flat-panel display technology, with funding provided by the Department of Energy, Department of Defense, and industry. All of the flat-panel efforts take advantage of LLNL expertise in lasers, optics, and materials science and state-of-the-art facilities.

Key Words: display, field-emission display (FED), laser, laser lithography, R&D 100 Award.

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*The group has been involved in two previous Livermore R&D 100 awards: the highly dispersive x-ray mirror in 1987 (Ceglio, Hawryluk, and Stearns) and the multilayer dielectric gratings for high-power lasers in 1994 (Boyd, Britten, and Perry).