Printed on
Recycled paper.

Science & Technology Review
Lawrence Livermore National Laboratory
P.O. Box 808, L-664
Livermore, California 94551

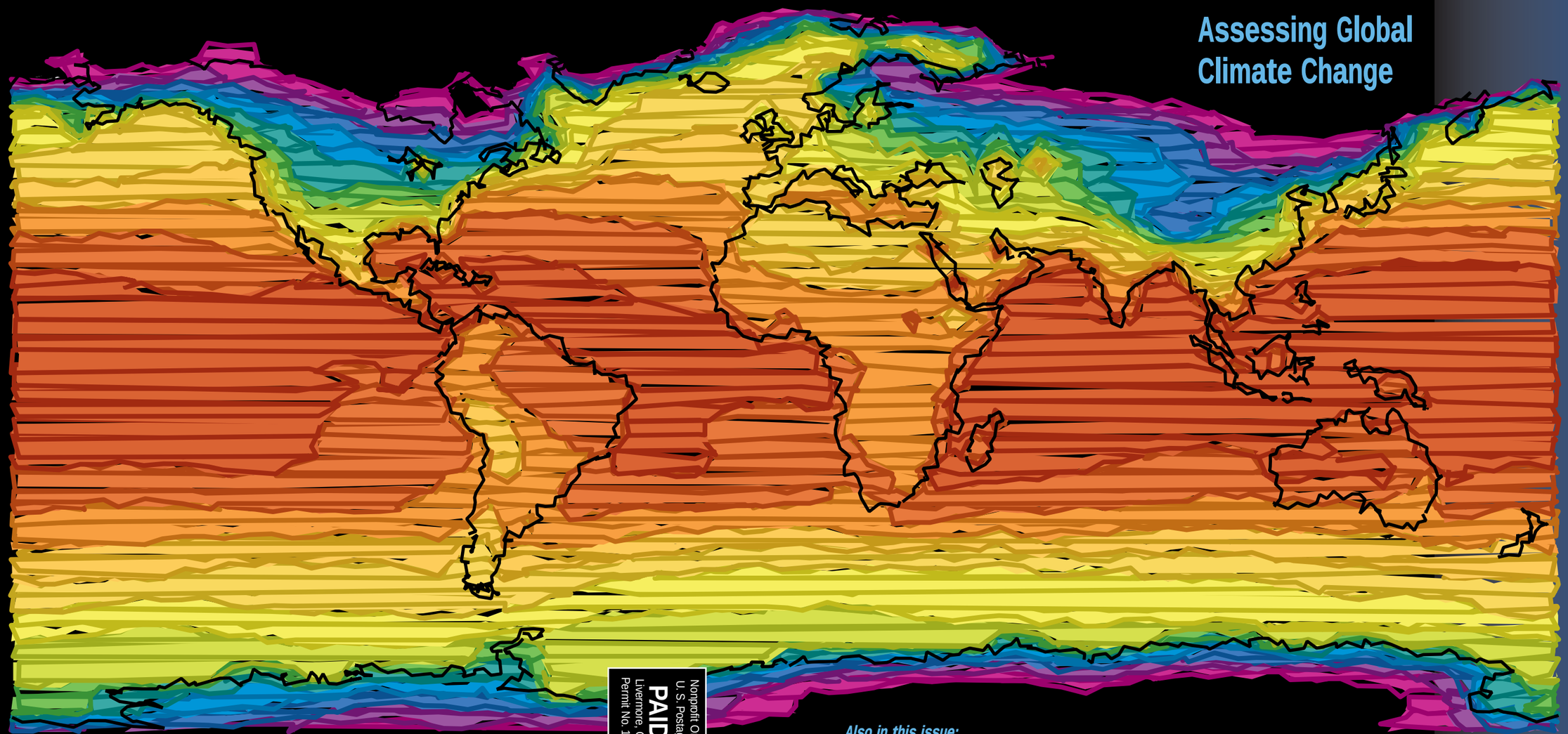
Nonprofit Org.
U. S. Postage
PAID
Livermore, CA
Permit No. 154

Science & Technology REVIEW

October 1996

Lawrence
Livermore
National
Laboratory

Assessing Global Climate Change

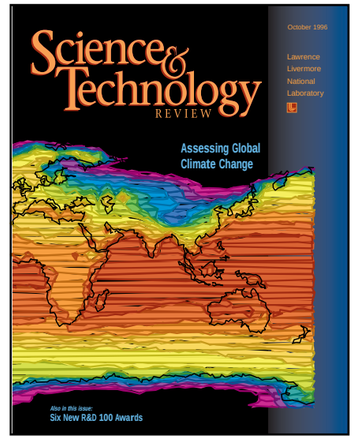


Also in this issue:

Six New R&D 100 Awards

About the Cover

The stylized map is taken from our feature article on global climate modeling, beginning on p. 6. The actual Figure 5a (p. 12) in the article shows the ten-year mean surface temperature variability in December, January, and February from 1979 to 1988. Using massively parallel processing computers at Livermore, the Laboratory performs calculations of this type in research coordinated with the international Atmospheric Model Intercomparison Project.



What Do You Think?

We want to know what you think of our publication. Please use the enclosed survey form to give us your feedback.

Electronic Access

S&TR is available on the Internet at *http://www.llnl.gov/str*. As references become available on the Internet, they will be interactively linked to the footnote references at the end of each article. If you desire more detailed information about an article, click on any reference that is in color at the end of the article, and you will connect automatically with the reference.

About the Review

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

S&TR Staff

Scientific Editors
Becky Failor and Ravi Upadhye

Publication Editor
Sue Stull

Writers
Arnie Heller, Dale Sprouse,
Katie Walter, and Gloria Wilt

Art Director
Kathryn Tinsley

Designers
Ray Marazzi and Kathryn Tinsley

Graphic Artist
Treva Carey

Compositor
Louisa Cardoza

Proofreaders
Ellen Shorr and Al Miguel

S&TR is a Director's Office publication, produced by the Technical Information Department, under the direction of the Office of Policy, Planning, and Special Studies.

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-52000-96-10
Distribution Category UC-700
October 1996

Science & Technology REVIEW

October 1996

Lawrence
Livermore
National
Laboratory

2 The Laboratory in the News

4 Patents

5 Commentary on the Importance of Climate Change

Feature

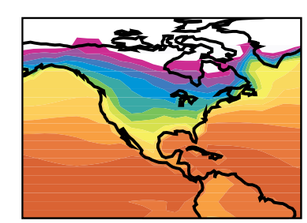
6 **Assessing Humanity's Impact on Global Climate**
Computation expertise developed at Livermore is being applied to the challenging task of understanding and predicting changes in global climate.

Research Highlights

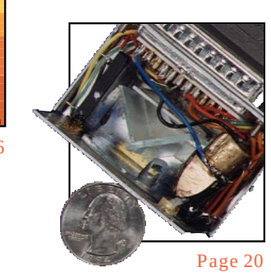
14 **Livermore Wins Six R&D 100 "Oscars"**
16 **Electronic Dipstick Signals New Measuring Era**
18 **Signal Speed Gets Boost from Tiny Optical Amplifier**
20 **SixDOF Sensor Improves Manufacturing Flexibility**
22 **A Simple, Reliable, Ultraviolet Laser: the Ce:LiSAF**
24 **Giant Results from Smaller, Ultrahigh-Density Sensor**
26 **Thinner is Better with Laser Interference Lithography**

28 Abstract

Page 24



Page 6



Page 20

Technique to hunt dark matter could search for planets

An astrophysics technique used to search for "dark matter" may prove valuable in finding planets orbiting suns near the center of our galaxy. That is the view of Laboratory scientists David Bennett and Sun Hong Rhie in a paper for the *Astrophysical Journal*.

Bennett is part of an international team that is searching for dark matter: nonvisible astrophysical objects—such as black holes, white dwarfs, brown dwarfs, and neutron stars—that are estimated to account for 90% of gravitational mass in our galaxy. Rhie is an expert on theoretical aspects of gravitational lensing by double stars and planetary systems.

In hunting for dark matter, astrophysicists use a method known as microlensing, in which gravity from a large dark object passing in front of a distant star makes the light from that star appear brighter for a time. This change in brightness can be graphed in the form of a light curve, typically a bell shape.

If the same search technique is oriented toward the center "bulge" of our galaxy, Bennett and Rhie say, faint stars could be used to microlens more distant and brighter stars. A planet associated with the faint star could then be detected within the resulting light curve. The planet would appear as a brief modulation of the bell-shaped curve.

The work by Livermore astrophysicists shows that an ambitious microlensing program could detect planets ranging from Jupiter down to the mass of less than ten Earths. While there are several other techniques for finding planets, microlensing appears to be the only ground-based technique that is sensitive to small planets.

Contact: David Bennett (510) 423-0656 (bennett3@llnl.gov) or Sun Hong Rhie (510) 423-0660 (sunhong2igpp.llnl.gov).

Livermore provides spectrometer to Poland

Polish border guards are in a better position to do on-the-spot analysis of suspicious materials entering or leaving their country, thanks to a portable gamma-ray spectrometer the Laboratory has provided by way of the Department of Energy and Department of State.

Before delivery of the device in June, the only way Polish border guards could analyze suspicious materials was by sending them off to the Polish Central Lab. At an international forensics conference last fall, the director of the Polish Central Lab voiced the need for a portable system, noting more than 100 border incidents involving suspicious materials in 1995.

The surplus spectrometer was provided by the Laboratory's Emergency Preparedness and Response Division, a unit of the Nonproliferation, Arms Control, and International Security directorate. In addition to tracking and analyzing materials at Polish border crossings, the spectrometer will be used for radiological monitoring.

Contact: Tom Smith (510) 422-8252 (smith77@llnl.gov).

Portable treatment system promises cleanup savings

Automated, portable groundwater treatment facilities developed by Laboratory scientists promise to save time and millions of dollars in environmental cleanup costs.

Spurring development of the portable treatment units is cleanup of groundwater beneath the Livermore site. Groundwater contamination is primarily volatile organic compounds largely left over from the time when the site was a naval air training station. There are five stationary treatment facilities currently in operation at the Livermore site, treating water pumped from 27 extraction wells.

Through geologic and geophysical analysis of subsurface conditions and the use of computer models, scientists can estimate the optimum locations for extraction wells that connect to surface treatment facilities. Because those locations change over the course of cleanup operations, the versatility of the new portable units will allow Livermore scientists to attack specific areas of contamination as the cleanup proceeds—at lower costs for the facility, piping, and manpower (for more information see *S&TR* Jan./Feb. 1996 and May 1996).

Laboratory remediation experts expect to save more than $10 million with the new portable facilities, which will substitute for previously planned stationary treatment facilities. The portable treatment approach is also expected to speed cleanup by allowing remediation experts to move the treatment systems easily to different locations to most efficiently remove the pollution.

Contact: Ed Folsom (510) 422-0389 (folsom1@llnl.gov).

Lab achieves chip production breakthroughs

Two breakthroughs by Laboratory researchers could help U.S. manufacturers produce computer chips with 1,000 times more memory than today's chips—and do so ten times faster than current technology.

The advances appear to largely overcome two critical hurdles that could have blocked the use of extreme ultraviolet (EUV) light to make computer chips in a process called EUV lithography. EUV lithography would allow 21st century computer chip makers to work with light wavelengths 20 times shorter than those of today's technology, reducing line widths or feature sizes on chips from 0.35 to 0.1 micrometer and smaller.

Lawrence Livermore's advances came in two key areas:

- A critical 20- to 50-fold improvement in accuracy for measuring the surface shapes of optical components used in the lithography process.
- A 300,000-fold reduction in the number of defects in the multilayer-coated reflective masks used to transfer circuit patterns onto silicon wafers, or chips.

The reduction in mask defects springs from an ion beam sputter deposition system developed by the Laboratory and Veeco Instruments Inc, a Plainview, New York, semiconductor equipment company.

Contact: Andrew Hawryluk (510) 422-5885 (hawryluk1@llnl.gov).

Lab conducts test of airborne multisensor pod

Researchers from the Laboratory's Nonproliferation, Arms Control, and International Security directorate conducted airborne tests earlier this year of a multisensor unit they developed to remotely detect small quantities of chemicals and radionuclides. Designed primarily for weapons treaty verification, the unit has potential applications in environmental monitoring or in the event of an industrial accident or natural disaster.

The 5-m-long by 1-m-wide cylindrical unit, designed to attach to the underside of an aircraft wing, is called the Effluent Species Identification (ESI) pod. A miniature laboratory, the pod contains four effluent sensors: an ion mass spectrometer for identifying chemicals, a radionuclide analyzer to detect radioactivity, a krypton sampler, and an aerial atmosphere sampler. Sensor guidance is provided by a target tracking system located in a small revolving turret on the underside of the pod.

Laboratory researchers developed one of the sensors and integrated it and the three others into the ESI pod, which they also developed. Collaborating with the Laboratory were Pacific Northwest National Laboratory and the Savannah River Technology Center. The pod is one of several being developed as part of the Department of Energy's Airborne Multisensor Pod System, a nonproliferation program involving several DOE laboratories, the U.S. Navy, and private industry.

Contact: Joe Galkowski (510) 422-0602 (galkowski1@llnl.gov).

Seeping gases can aid detection of nuclear tests

Tiny amounts of radioactive rare gases that seep to the surface from underground nuclear explosions could foil nations secretly trying to evade a proposed ban on nuclear tests. This finding by Lawrence Livermore scientists offers international agencies another possible tool for monitoring a nuclear weapons test ban.

In the August 8 issue of the British journal *Nature,* the scientists reported that gases produced by nuclear explosions and released along natural faults and cracks in the Earth can be used to detect clandestine nuclear tests.

The finding is based on an experiment conducted in 1993 at the Department of Energy's Nevada Test Site. In the experiment, the Lawrence Livermore team mixed small amounts of two nonradioactive gases, helium-3 and sulfur hexafluoride, into chemical explosives in a non-nuclear test that simulated a deeply buried underground nuclear explosion.

Says geophysicist Charles Carrigan, who led the Livermore team: "Our experiment shows that people who attempt to conduct a clandestine nuclear test will not have any guarantee they can hide it from detection during an on-site inspection."

Contact: Charles Carrigan (510) 422-3941 (carrigan2@llnl.gov).

Patents

Each month in this space we report on the patents issued to and/or the awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Thomas E. McEwan George D. Craig	**Ultra-Wideband Receiver** U.S. Patent 5,523,760 June 4, 1996	A single-ended ultra-wideband receiver with a self-regulating amplifier that maintains a predetermined average output voltage. An input channel is connected to one input of the amplifier and a strobe generator is connected to the input channel. A single Schottky detector diode or a pair of series-connected Schottky detector diodes are placed in the input channel.
Bernhard Rupp	**Electrorheological Crystallization of Proteins and Other Molecules** U.S. Patent 5,525,198 June 11, 1996	The process of producing an electrorheological crystalline mass of a molecule by dispersing the molecule in a fluid and subjecting the molecule dispersion to a uniform electrical field for a period of time during which the electrorheological crystalline mass is formed. Crystallization is performed by maintaining the electric field after the electrorheological crystalline mass has formed, during which at least some of the molecules in the mass form a crystal lattice.
Rajeev R. Rohatgi Thomas E. Cowan	**Fan-Fold Shielded Electrical Leads** U.S. Patent 5,525,760 June 11, 1996	Electrical leads that are shielded, vacuum- and cryogenic-temperature-compatible, totally nonmagnetic, and bakable. They are suitable for multiple signal and/or multiple layer applications, and the leads are suitable for voltages in excess of 1,000 volts. The assembly is easily fabricated by simply etching away certain areas of a double-clad substrate to form electrical leads on one side.
Brian D. Andresen Joel D. Eckels James F. Kimmons David W. Myers	**The Portable Gas Chromatograph–Mass Spectrometer** U.S. Patent 5,525,799 June 11, 1996	An organic chemical-analysis instrument that has sensitivity and mass resolution characteristics of laboratory benchtop units, but is portable and has low electrical energy consumption. The instrument weighs less than 32 kilograms and uses less than 600 watts at peak power. The instrument incorporates a modified commercial quadrupole mass spectrometer to achieve the instrument sensitivity and mass resolution, comparable to larger laboratory instruments.
T. Hayden Stephen A. Payne Joseph S. Hayden John H. Campbell Mary Kay Aston Melanie L. Elder	**Phosphate Glass Useful in High Energy Lasers** U.S. Patent 5,526,369 June 11, 1996	A laser system using phosphate laser glass components having an emission bandwidth of >26.29 nm and a coefficient of thermal expansion, from 20 to 300°C of <145 ¥ 10^{-7}/K. The laser glass components consist of a multioxide composition, Al_2O_3 for chemical durability and thermal mechanical properties, and K_2O. The system operates at an energy level of <0.1 MJ. The glass is desirable for laser operation and manufacturing.
Georg Albrecht E. Victor George William F. Krupke Walter Sooy Steven B. Sutton	**High Energy Bursts from a Solid State Laser Operated in the Heat Capacity Limited Regime** U.S. Patent 5,526,372 June 11, 1996	A heat-capacity laser operating in two modes: a firing cycle and a cooling cycle. In the firing cycle the solid-state laser is not cooled. In heat capacity operation, as lasing proceeds, the active medium will heat up until it reaches a maximum acceptable temperature. The waste heat is stored in the active medium itself. After lasing is complete, the active media are cooled to the starting temperature, and the laser is ready to fire again.
James L. Kaschmitter Steven T. Mayer Richard W. Pekala	**Carbon Foams for Energy Storage Devices** U.S. Patent 5,529,971 June 25, 1996	A double-layer capacitor of carbon foam electrodes. Several foams may be produced—including aerogels, xerogels, and aerogel-xerogel hybrids—that are high-density, electrically conductive, dimensionally stable, and machinable. The electrodes are formed from machinable, structurally stable carbon foams derived from the pyrolysis of organic foams. Integration to form the capacitor is achieved using lightweight components.

Commentary by Jay C. Davis

The Importance of Climate Change

ONE grand challenge facing the international scientific community is determining the record of the Earth's climate since the last ice age and assessing whether humans have significantly impacted the climate in recent years. If we conclude with confidence that human activities do indeed affect climate and that the consequences pose real dangers, responding to such dangers will present tremendous political and economic challenges to every nation. Working on such a problem is a worthy mission for a national laboratory; Livermore's multidisciplinary expertise enables us to contribute substantive solutions.

Our understanding of climate variability has increased greatly over the past few decades because the record of climate since the last glaciation has been developed through studying sediments from melting episodes in ice sheets and ice caps, and pollen, dust, and isotopic records in ice caps and lake and river sediments. We have come to appreciate that we live in a system that has experienced great temperature and precipitation swings in the recent millennia.

A consequence of this insight is that interpreting global warming in simple terms such as an average warming of a fraction of a degree Celsius over the Earth's surface could greatly underestimate the actual effects. Change will have a regional pattern, causing warming in some regions and cooling in others, as global patterns of precipitation and other atmospheric variables shift. In particular, any perturbation of the ocean currents that make up the thermohaline cycle (believed to be stable for the past several thousand years) could produce dramatic regional thermal effects such as cooling Europe by several degrees Celsius and drying the center of the North American continent.

We know from both the historical and archaeological records about events such as the Little Ice Age in Europe and hundred-year droughts in North and South America. If our actions produce similar climate change, the human consequences—ecological, political, and economic—could rival any natural disaster in human record. But before worrying too much about disasters, we must have more information.

The attribution of climate change to human activities, coupled with increasing confidence (now not available) in the ability to predict the effects of climate change, will lead to the need to evaluate the options, costs, and credibility of measures to mitigate the effects of such change. This evaluation will require an unprecedented combination of scientific, economic, and policy skills to reassure the political system if the consensus required to modify the economies of the developed world and the path of the developing world is to be achieved. Unprecedented confidence in the reliability of scientific assessments will be necessary.

The work described in this issue beginning on p. 6 summarizes several LLNL research projects that have advanced our understanding of the climatic consequences of human activities and increased our confidence to detect climate change and determine if it is linked to humans. We have shown that the burning of fossil fuel that increases atmospheric carbon dioxide and causes warming globally also injects sulfate aerosols that promote local cooling. This knowledge makes it possible to predict patterns of global warming and cooling from signatures that are associated with human activities.

In developing tools for testing climate models, we have statistically compared the past climate record with predictions based on fossil fuel consumption records. We found remarkably suggestive agreement in the geographic patterns of warming and cooling. While these results are currently the subject of controversy regarding the evaluation processes of the Intergovernmental Panel on Climate Change, there is strong consensus within the scientific community that the data suggest a human origin for the global warming that is currently being observed.

Livermore's strengths and role in climate studies come from several capabilities. We are conducting an international program to create standard data records and methodologies to test the credibility of climate models. Our scientists study inadequately characterized mechanisms of climate such as atmospheric chemistry, aerosol, and radiation effects, and they develop models that allow realistic coupling of atmospheric and ocean processes. Modeling activities grow with collaborations such as the Accelerated Strategic Computing Initiative (ASCI), which links us to new computational capabilities within the Department of Energy. Measurements of the carbon-14 record of the modern carbon cycle and the isotopic records of the paleoclimate are provided by projects conducted at our Center for Accelerator Mass Spectrometry.

Together, our powerful computational, modeling, and measurement capabilities give us the confidence that Lawrence Livermore will continue to play a major role in responding to this critical scientific challenge.

■ Jay C. Davis is the Associate Director for Environmental Programs.

Assessing Humanity's Impact on Global Climate

Capitalizing on strengths in computer modeling, Livermore researchers are working to provide policy makers a quantitative picture of our changing global climate.

EARTH returns the Sun's heat to space in the form of thermal infrared radiation. But atmospheric carbon dioxide (CO_2) and trace gases help keep our planet warmer than it otherwise would be by absorbing some of this radiation, thus blocking its escape. Human activities, especially the burning of fossil fuels, can intensify this natural greenhouse effect by pumping increased levels of CO_2 and other so-called "greenhouse gases" into the atmosphere.

Do these activities mean that our climate will become noticeably warmer, with a rate of warming (and accompanying changes to other climatic parameters like rainfall and sea level) great enough to harm human societies and natural ecosystems?

Other than waiting for the future to happen, the only means to answer this question is with computational modeling—specifically with general circulation models (GCMs) that simulate weather and climate in detail around the world. For something as complex as the climate system, these models are typically complex as well. These elaborate computer programs require the utmost in machine performance because they incorporate other state-of-the-art models of key physical processes affecting climate.

At Lawrence Livermore National Laboratory, we are applying computation expertise—originally developed to simulate nuclear explosions—to the challenging task of climate modeling. We also make use of Livermore expertise in atmospheric science that grew out of efforts to model fallout from nuclear explosion testing. These model-building and simulation efforts in climate studies are synergistic with other Laboratory programs, in that they all advance sophisticated techniques for programming simulation models on state-of-the-art computers.

While the increase of atmospheric CO_2 since the Industrial Revolution 200 years ago is apparent from geologic and instrumental records, it is not so obvious that a warmer climate has resulted (Figure 1). The Earth's surface has warmed slightly, on average, over the last century. So far, the increase is irregular and small, particularly when compared with GCM-based predictions of 21st century global warming, but not small compared to predictions of warming expected to date. The data also show that human production of CO_2 will not be the only factor in global temperature change.

Three Decades of Work

Global climate research has been a part of our work at Lawrence Livermore for three decades. (See *Energy & Technology Review*, September 1984, for a description of past work.) Today, we play a leading role in climate research, as is appropriate for a Department of Energy laboratory with missions that include studying the use of fossil fuels and their potential impact on global and regional environments.[1]

At Lawrence Livermore, our goal is to better understand global climate and humanity's impacts on it. Most of the Laboratory's global climate work is done in the Environmental Programs Directorate. The directorate's Atmospheric Sciences Division develops and applies climate models that represent key processes affecting the atmosphere, oceans, and biosphere. Using these complex models, we seek to improve scientific understanding of the mechanisms of global change in the environment and climate.

Our major climate research efforts are directed toward:

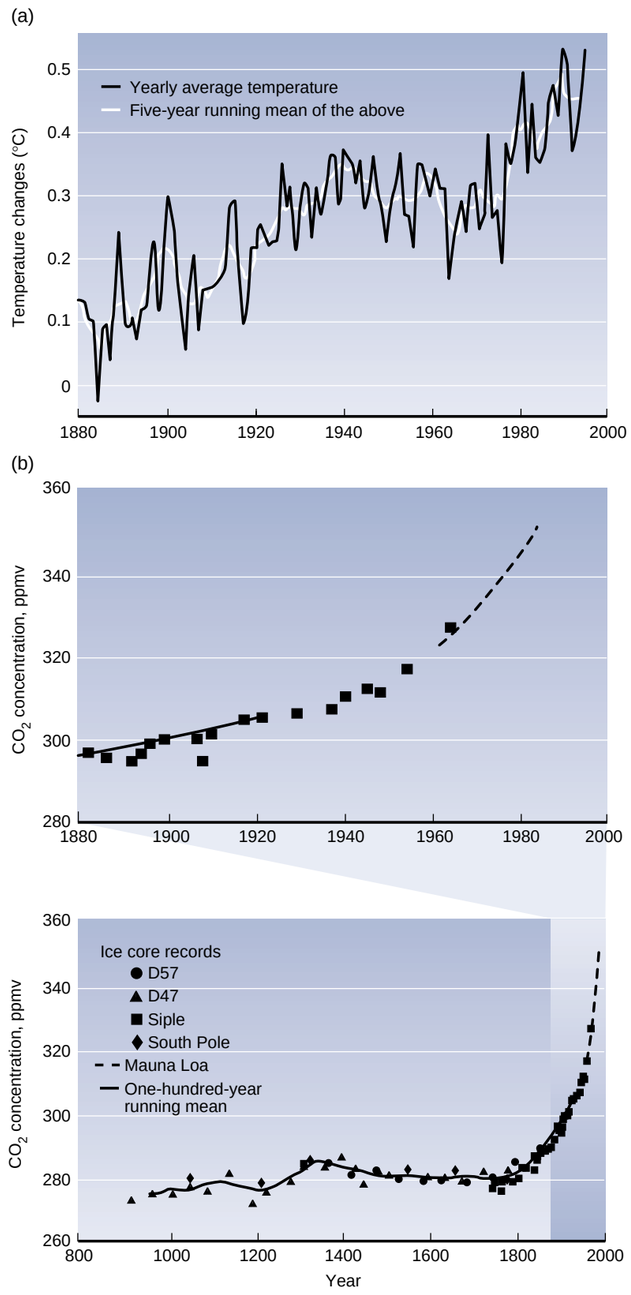
- Assessing the effects of aerosols.
- Modeling the carbon cycle.
- Applying advanced computing techniques.
- Finding the limits of climate predictability.

In these studies, climate researchers from other Laboratory areas are also involved, such as those in the Program for Climate Model Diagnosis and Intercomparison (PCMDI), who document climate model performance in order to reduce systematic errors (see box, p. 10).

Assessing Aerosol Effects

In recent years, we have been addressing the apparent disparity between the GCM predictions of global warming and the observational record. According to the models, greenhouse gases such as CO_2 should have raised average temperatures worldwide by 1°C during the past 100 years. Instead, temperatures climbed by about only half a degree, as shown in Figure 1.

One hypothesis to explain the disparity states that atmospheric sulfate aerosols might partially offset the



effects of greenhouse gases. Suspended in the atmosphere, these micrometer-size particles tend to cool the Earth by scattering sunlight back into space. The aerosols result from photochemical reactions of sulfur dioxide emitted into the atmosphere through the combustion of fossil fuels.

To test that hypothesis, we developed the world's first global chemistry–climate model. This model involved combining three others: (1) the LLNL version of an atmospheric model developed by the National Center for Atmospheric Research for use by the global climate research community, (2) a simple ocean model that represents conditions of the ocean's upper layers (within 50 meters from the surface), and (3) the GRANTOUR tropospheric chemistry model developed at Livermore. GRANTOUR simulates the transport, transformation, and removal of various sulfur species in the troposphere (lowest 10 to 20 kilometers of the atmosphere). It was needed for predicting the formation of sulfate aerosols from sulfur dioxide gas released into the atmosphere.

We used the chemistry–climate model in a series of experiments that were the first attempt to simulate how temperatures are affected by combinations of carbon dioxide and sulfate aerosols.[4] Numerical integrations began with a control run using the pre-industrial CO_2 level and no sulfur emissions. Next, we ran an experiment to simulate CO_2 increased to the present-day carbon dioxide level and examined the difference in temperature compared to the control run (Figure 2a). The next run combined CO_2 and sulfate aerosols, and again we

Figure 1. (a) On average, the Earth's surface has warmed slightly over the last century.[2] (b) CO_2 concentrations over the past 100 and 1,000 years from Antarctica ice-core records and (since 1958) Mauna Loa, Hawaii, measurement site.[3]

considered the difference compared to the control run (Figure 2b). These two sets of results can be compared to the observed temperature changes. Figure 2c depicts the difference between temperature data taken in 1948 and 1988. The run depicted in Figure 2b, which included both CO_2 and sulfur emissions, predicted results much closer to the temperature difference map, which is based on observations.

These results showed that the sulfate aerosols offset CO_2-induced warming and could even produce net cooling in regions of the Northern Hemisphere where sulfur emissions are highest.[4] Follow-up statistical studies found that the patterns of climate change resulting from both greenhouse gases and sulfate aerosols are a closer match to actual observed temperatures than patterns of change predicted by models that only include greenhouse gases.[5,6]

These Laboratory results are included in a United Nations report prepared by the Intergovernmental Panel on Climate Change.[3] That report, written by dozens of internationally prominent scientists including several from Lawrence Livermore, contains the most recent model-generated predictions of temperature change to the year 2100 (an increase between 1 and 3.5°C) and includes the presence of both sulfate aerosols and greenhouse gases. The sulfate aerosols counteract global warming to some extent; however, the potential warming that the report describes may still be significant enough to pose a threat to human economies and natural ecosystems. Also, it is important to note that greenhouse gases remain in the atmosphere far longer than sulfate aerosols, and thus their effects would dominate even more if present sulfur and greenhouse emission rates continue.

Modeling the Carbon Cycle

Most of the carbon dioxide added to the atmosphere by human activities results from burning fossil fuels,

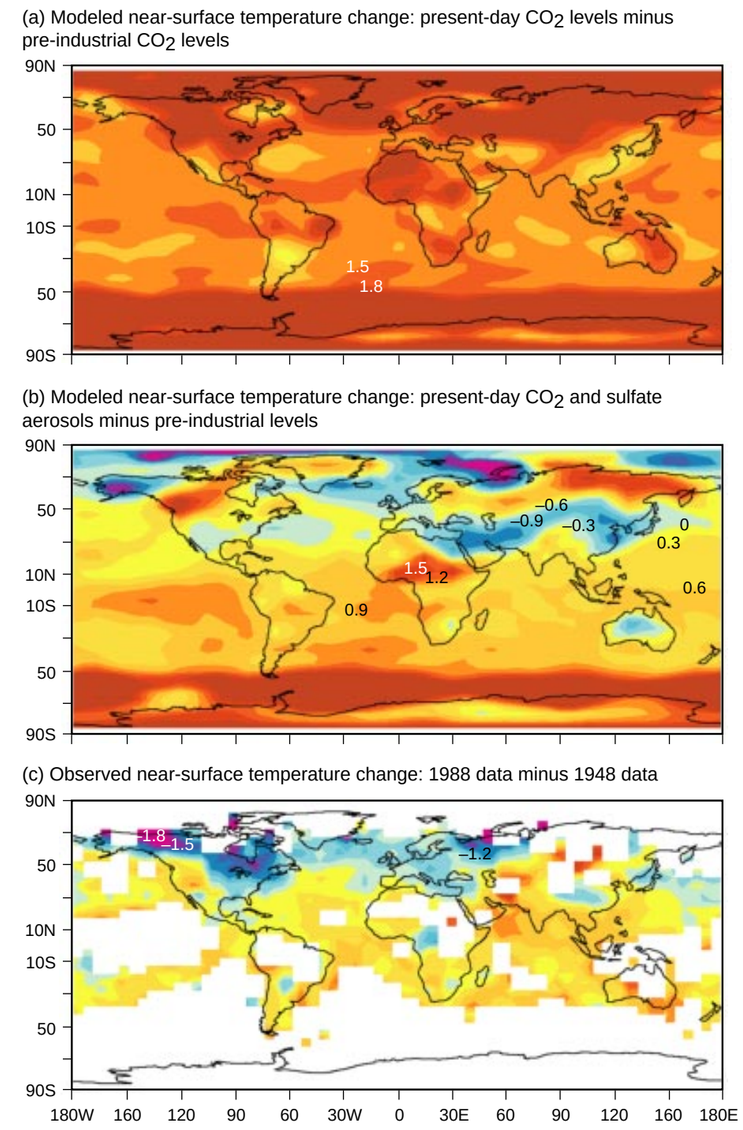


Figure 2. Temperature-change maps show that observed patterns of near-surface temperatures are in better accord with predictions from models that consider CO_2 and sulfur emissions than with models that consider CO_2 only. Notes: all temperature changes are for Sept., Oct., and Nov. in °C; white areas in (c) indicate missing data.

PCMDI: Reducing Systematic Model Errors

Diagnosing why climate models behave the way they do is a nontrivial task: as models have become more complex, the disagreement among them—as well as that between models and observations[7]—remains significant, yet poorly understood. The Laboratory established the Program for Climate Model Diagnosis and Intercomparison (PCMDI) in 1989 to develop improved methods and tools for evaluating global climate models.

As part of its mission, the PCMDI is coordinating the Atmospheric Model Intercomparison Project (AMIP) on behalf of the international World Climate Research Programme. In this project, virtually all of the world's 30 atmospheric modeling groups are simulating the climate of recent decades, using observed sea surface temperature as a boundary condition.

AMIP has already gained substantial insight into atmospheric models.[8] For the first time, disagreement among models can be assessed precisely. For example, PCMDI researchers have found that the models generally agree well in their predictions of temperature and winds but disagree widely in their predictions of clouds. Systematic errors common to all models have also been revealed, e.g., discrepancy between predicted and observed absorption of solar energy in clouds.

In addition to its work for the AMIP, the PCMDI has entered into a project with the World Climate Research Programme to compare the performance of various coupled ocean–atmosphere–sea-ice models. These more complete models are being used in forecasts of 21st century global temperatures.

The PCMDI also has provided tools and information to facilitate climate model analysis. These include model documentation, a database of observations for comparison with model output, and a visualization and computation system for both model-produced and observed climate data.

although substantial amounts of CO_2 (20%) result from less plant absorption due to deforestation. Only about half the CO_2 that is released into the atmosphere remains there, however, and what happens to CO_2 that does not remain in the atmosphere is uncertain. As carbon dioxide comes in contact with the sea surface, some is absorbed into the ocean; as it comes in contact with the leaves of plants, some is absorbed and transformed into plant tissue. However, the amounts and rates at which the sea or plants can absorb CO_2 are still poorly characterized. Hence, our models cannot adequately predict how much of the approximately 6 billion tons per year of CO_2 that is released today from human activities will be found in the ocean, in plants, or in the atmosphere 10, 20, or 100 years from now.

We must narrow these uncertainties in order to make reliable predictions of the climatic consequences of fossil fuel burning and deforestation. To do this, we are developing a carbon-cycle model that includes transport of CO_2 in the atmosphere, the consumption and respiration of CO_2 by terrestrial ecosystems, and the absorption and emission of CO_2 by the oceans. The model incorporates a treatment of carbon isotopes that is more detailed than can be found in any other global carbon-cycle model. Carbon isotope data from biomass and ice samples tested at facilities such as LLNL's Center for Accelerator Mass Spectrometry are contributing to our confidence in the model's predictive capability. Computer experiments using an initial version of this model show that simulations of changes in carbon storage over the past two centuries are consistent with our understanding of the history of deforestation and with observed changes (see Figure 3).

The oceanic portion of our carbon-cycle model incorporates models of ocean circulation, chemistry, isotopic processes, and biology. We use a state-of-the-art ocean GCM with a dynamic and thermodynamic sea-ice model that runs on massively parallel computers. This GCM model shows how dissolved carbon dioxide and other chemicals impact the carbon cycle; it includes global distributions of natural and nuclear-explosive-produced radiocarbon. With this model, we have simulated oceanic absorption of carbon for the past few centuries. To our knowledge, this is the first completed ocean biogeochemistry model in use today.

The terrestrial ecosystem portion of our carbon cycle model, still under development, is based on a detailed model of how a terrestrial ecosystem functions and on a detailed simulation of biochemical processes that occur during photosynthesis. Already widely published, the model successfully simulates carbon fluxes at specific sites where detailed measurements have been made. As a consequence, the terrestrial portion is considered by many to be the model of choice for application to forest growth rates. The fact that this model is physically based and well tested gives us confidence that we will be able to incorporate it into the larger carbon-cycle model.

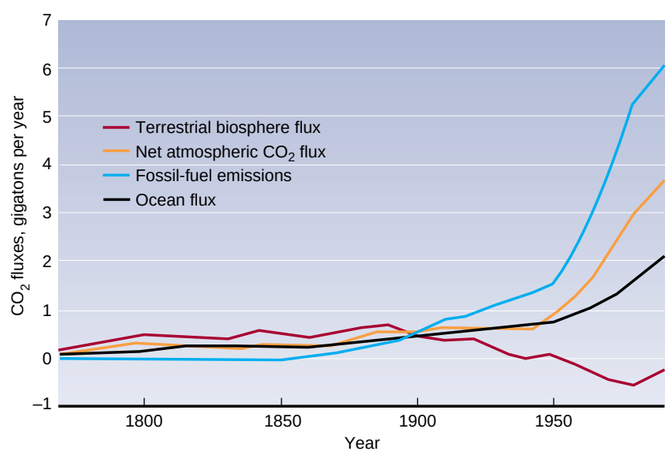


Figure 3. Carbon dioxide fluxes into and out of the atmosphere. The red curve shows that the terrestrial biosphere (plants and soils) was a net absorber of carbon from the atmosphere until about 1950. The observed yearly change in the carbon content of the atmosphere (gray line) is equal to the measured fossil-fuel emissions (pink line) plus the modeled flux of carbon into or out of the ocean (black line) plus the residual flux into or out of the terrestrial biosphere (red line). Accuracy of this residual CO_2 value is dependent on the accuracy of the measured or modeled data comprising the other terms.

Applying Advanced Computing Techniques

Typical atmospheric GCMs calculate temperature, pressure, wind velocity, and dozens of other variables at millions of points around the globe. Each calculation must be repeated to advance the simulated climate hour by hour. However, the cost of computational time severely limits the use of GCMs, even on the fastest of today's supercomputers.

To address this problem, the DOE established the Computer Hardware, Advanced Mathematics, and Model Physics (CHAMMP) Program. With support from CHAMMP, we modified an atmospheric GCM to run on the new-generation computers that promise significantly greater speed. Our modified GCM is specifically designed to run on massively parallel processing computers that simultaneously employ large numbers of arithmetic processors with memory distributed locally to each.

We have used a technique known as domain decomposition to distribute the calculation across many processors. As shown in Figure 4, the basic idea is to divide the grid points covering the planet into rectangular "tiles," or subdomains. Each of these subdomains is assigned

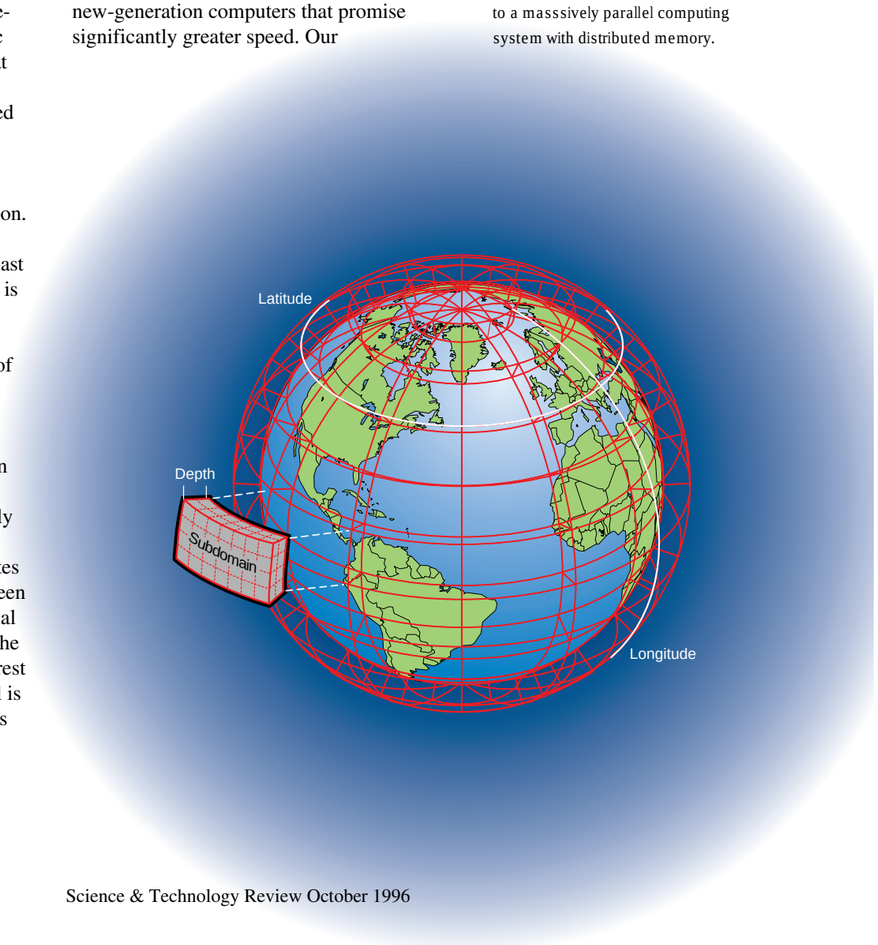


Figure 4. LLNL scientists use this two-dimensional domain decomposition of the globe to accomplish an efficient distribution of climate-model calculations to a masssively parallel computing system with distributed memory.

to a processor. A particular processor is responsible for advancing the solution only for those grid points contained within its subdomains. To do this, however, requires information about the state of the grid points just outside the subdomain. Interprocessor communication of this data surrounding the subdomain is accomplished on the computer's internal network via explicitly programmed message-passing techniques. Our challenge is to minimize this communication yet ensure that all available processors are assigned roughly equal amounts of work.

We perform both atmospheric and oceanic GCM calculations very rapidly as a result of the availability of the Cray T3D and other massively parallel machines at Livermore. In the largest series of calculations to date, we performed an ensemble of 20 simulations for the Atmospheric Model Intercomparison Project (see box, p. 10). Different calculations varied only in their initial conditions, allowing an assessment of the natural variability of climate due to the inherently chaotic nature of the atmosphere. Understanding such natural variability will allow better climate system predictions (Figure 5). We are analyzing this ensemble data and preparing it for dissemination to the wider climate modeling community.

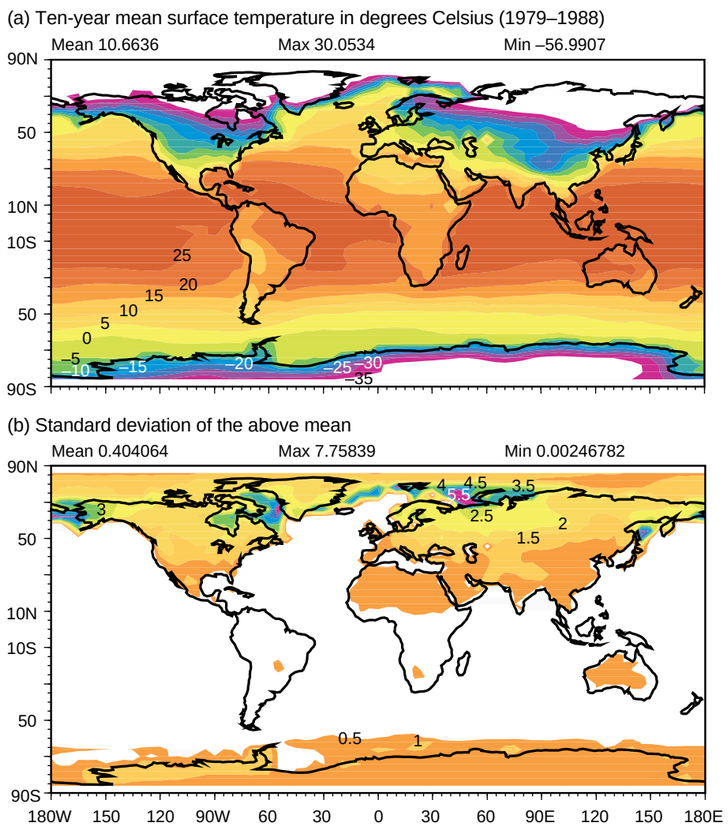


Figure 5. Temperature variability in the AMIP ensemble of 20 simulations. These maps show (a) the December–January–February mean surface temperature and (b) the variability as characterized by the standard deviation of the mean temperature. The standard deviation, not uniform over the globe, is largest in the extreme high latitudes, which are characterized by snow-covered land and sea ice.

Research Challenges

Progress toward a predictive understanding of global climate change depends on our ability to improve the computer simulations we use. This process is sometimes slow and occasionally controversial. The computer simulations are very complex because the processes that determine climate are nonlinearly coupled across a wide spectrum of space and time scales. For validation, we must rely on laboratory-scale experiments—which can shed light on isolated, individual processes—and on extensive field measurement programs to gather essential observational data. It is only with controlled simulations that we can explore the myriad "what if" scenarios.

One particularly important question that we now can address involves the predictability of the climate system. Short-term weather predictions are fundamentally limited by the chaotic behavior of the atmosphere: no matter how perfect the forecast model, the weather cannot be predicted beyond a few weeks. This is because even small errors in initial conditions—which are always present, because of limited precision and spatial resolution of observational data—are amplified by the turbulent nature of the atmospheric flow so that the statistical significance of the forecast is diminished after a few days.

We assume that the more general characteristics of climate can be predicted for considerably longer periods of time. However, the climate system may have very long time scales of natural variability, originating in part from the nature of large-scale ocean circulation patterns. In this context, it becomes difficult to discriminate between systematic effects (such as possible global warming) and low-frequency natural climate variations. Finding the limits of natural climate predictability in this sense is obviously a prerequisite to making useful predictions of possible anthropogenic effects. Experiments with fully coupled models, analogous to our ensemble work with the AMIP, are a first step in this direction.

We are also very interested in determining the possible impact of global climate change on scales of direct practical importance, on the order of tens to hundreds of kilometers (regional scales). It is on these scales that possible impacts on managed and natural ecosystem and water resources, for example, would be most apparent. This research is in a very early stage, but it will play an increasing role in the future. One approach that we will pursue is to use the global-scale climate model output to drive regional-scale models of hydrologic and ecological processesand thus capture local effects due to variations in topography, land use, and soil properties.

Such studies require world-class, high-performance computing capabilities, a multidisciplinary teamwork approach, and long-term institutional commitment. With new computing resources based on the knowledge we are gaining from collaborations such as ASCI, the Laboratory is positioned to continue making important and unique contributions to the science base of global climate research and to assist in the assessment of the consequences of potential climate change.

Key Words: Atmospheric Model Intercomparison Project (AMIP), carbon cycle, carbon dioxide, climate modeling, global climate, global climate model, greenhouse effect, massively parallel computers, sulfate aerosols.

Notes and References

1. See the July 1995 issue of *Science & Technology Review*, pp. 28–30, for additional LLNL work in regional climate modeling.
2. J. Hansen *et al*., "Global Surface Air Temperature in 1995: Return to Pre-Pinatubo Level," *Geophysics Research Letters* **23** (1996), pp. 1665–1668.
3. J. T. Houghton *et al*. (Eds.), *Climate Change 1995: The Science of Climate Change* (Cambridge University Press, Cambridge, 1996).
4. K. E. Taylor and J. E. Penner, "Response of the Climate System to Atmospheric Aerosols and Greenhouse Gases," *Nature* **369** (June 30, 1994).
5. B. D. Santer *et al*., "A Search For Human Influences on the Thermal Structure of the Atmosphere," *Nature* **382** (1996), pp. 39–46.
6. B. D. Santer *et al*., "Towards the Detection and Attribution of an Anthropogenic Effect on Climate," *Climate Dynamics* **12** (1995), pp. 77–100.
7. W. L. Gates, "AMIP: The Atmospheric Model Intercomparison Project," *Bulletin of the American Meteorological Society* **73** (1992), pp. 1962–1970.
8. W. L. Gates (Ed.), *Proceedings of the First International AMIP Scientific Conference* (Monterey, California, May 15–19, 1995), World Meteorological Organization Report WMO/TD-No. 732 (WCRP-92) (1996).
9. D. N. Williams and R. L. Mobley, "The PCMDI Visualization and Computation System (VCS): A Workbench for Climate Data Display and Analysis," *Program for Climate Model Diagnosis and Intercomparison, Report No. 17*, Lawrence Livermore National Laboratory, Livermore, California, UCRL-ID-116890 (1994).

For further information contact William Dannevik (510) 422-3132 (dannevik1@llnl.gov).

About the Scientist

WILLIAM P. DANNEVIK is the Atmospheric Sciences Division leader, a position he has held since 1995. He came to Lawrence Livermore in 1988, as a member of the A-Division code group. Dannevik received his B.S. in engineering science from the University of Texas in 1969 and his Ph.D. from St. Louis University in atmospheric science in 1984. In previous positions, he led an engineering consulting firm from 1974 to 1980 and was on the research staff of the Princeton University program in applied and computational mathematics from 1984 to 1988. He has published articles on computational fluid dynamics, boundary layer meteorology, high-performance climate simulation, and turbulence theory and modeling in the *Journal of Scientific Computing, Physics of Fluids, Atmospheric Environment, Parallel Computing, Journal of Supercomputing, Computer Physics Communications,* and *Plasma Physics and Controlled Fusion Research.*

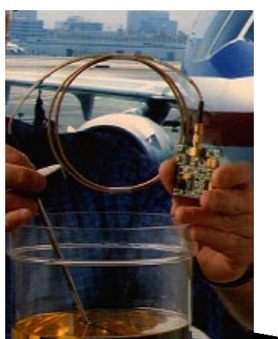
Livermore Wins Six R&D "Oscars"

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.

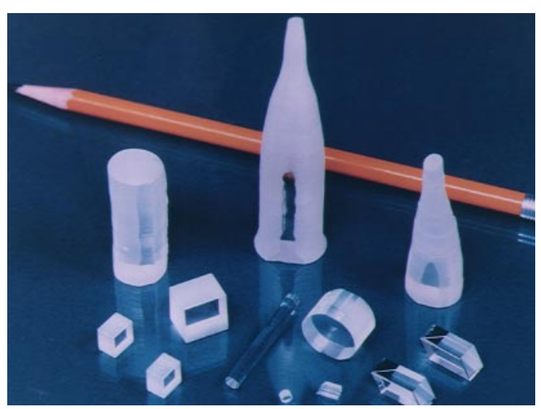
Two of this year's Laboratory winners stem from partnerships with American industry. Karena McKinley, acting director of the Laboratory's Industrial Partnerships and Commercialization office, says, "It is always a pleasure to see the industrial community recognize Laboratory work that has sprung from 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:

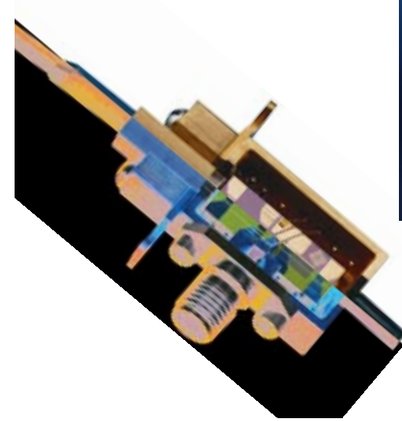
- The latest micropower impulse radar (MIR) application is an electronic dipstick to sense the level of fluid or other material stored in tanks, vats, and silos. It can also be used in automobiles to read levels of a variety of fluids. The dipstick is impervious to condensation, corrosion, or grime on 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.

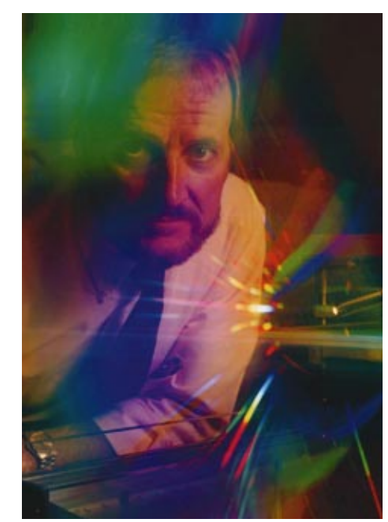


- A small, noncontact optical sensor will improve the manufacturing processes that employ robots by eliminating the time-consuming and expensive process of "teaching" robotic machinery new motions when manufacturing changes are required. This six-degrees-of-freedom (called SixDOF) sensor can sense its 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.

For further information contact Karena McKinley (510) 422-6416 (kdm@llnl.gov).





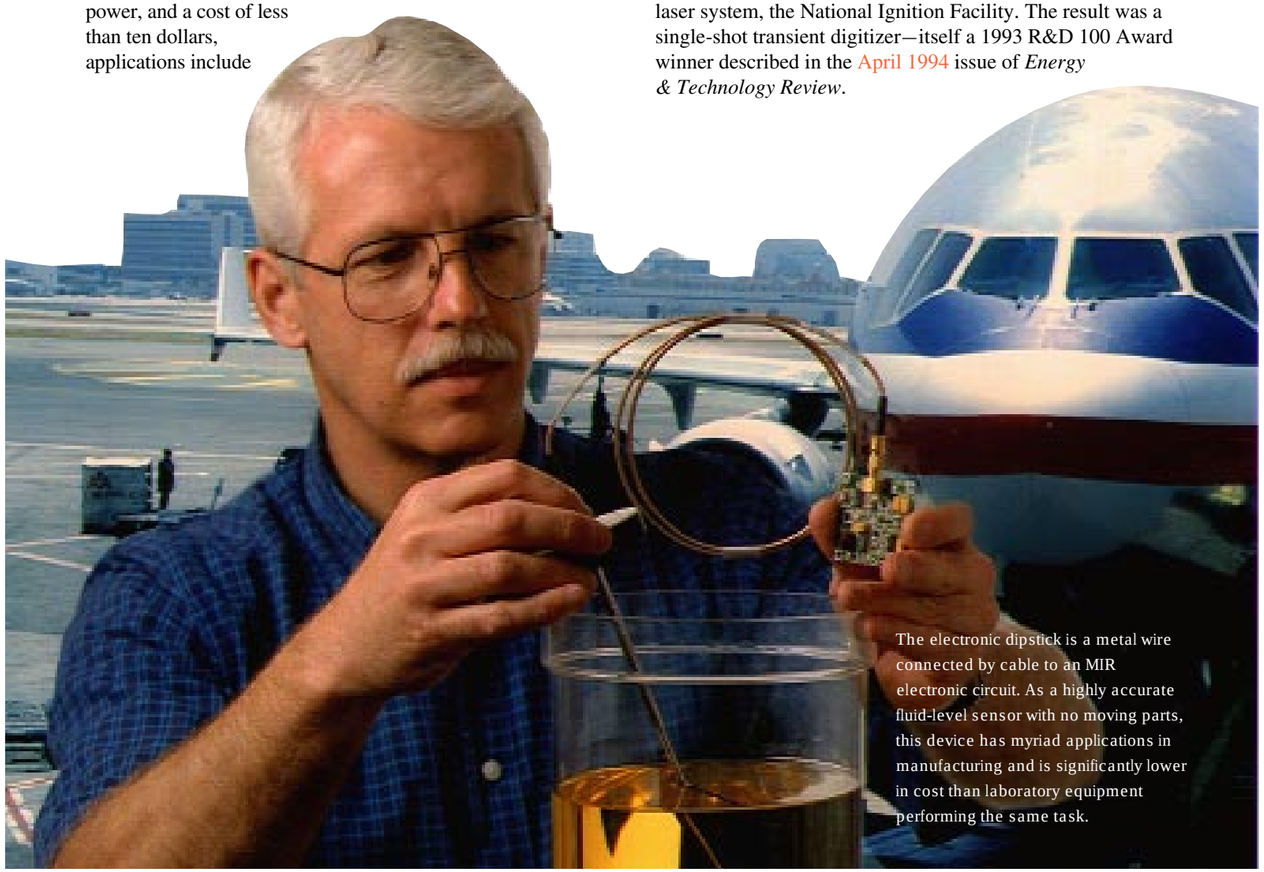
Electronic Dipstick Signals New Measuring Era

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.

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 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.

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.

For further information contact:
Thomas McEwan (510) 422-6935 (mcewan@llnl.gov).

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.

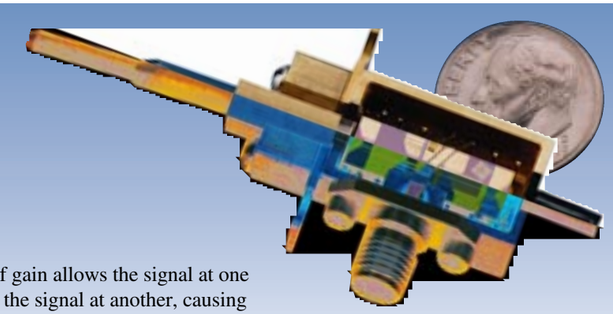
Team members sharing the award for the miniature optical amplifier include (from left, front) inventors Sol DiJaili and Frank Patterson; (rear) fabrication techs William Goward and Holly Petersen, program leader Mark Lowry, and inventors Jeff Walker and Robert Deri.

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.



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.

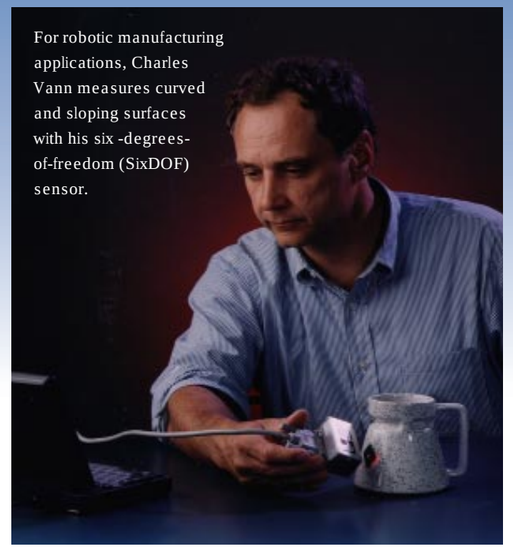
Looking farther into the future, if tiny, inexpensive optical amplifiers provide the broad signal bandwidth needed to transmit visual images as well as computer data, many people may someday work in "virtual offices" in their homes. Via two-way video, they will be able to confer with colleagues, participate 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.

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) .

SixDOF Sensor Improves Manufacturing Flexibility



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

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-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.

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.

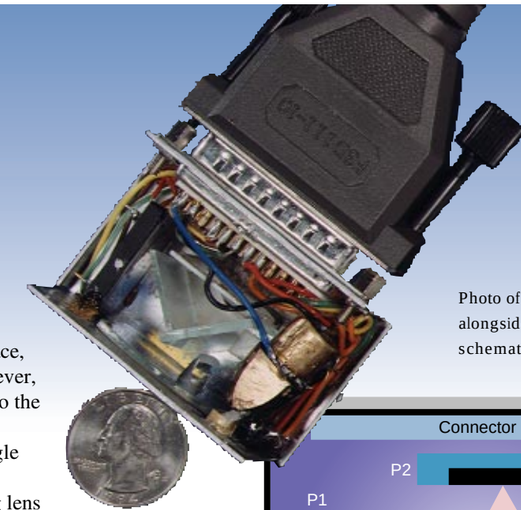
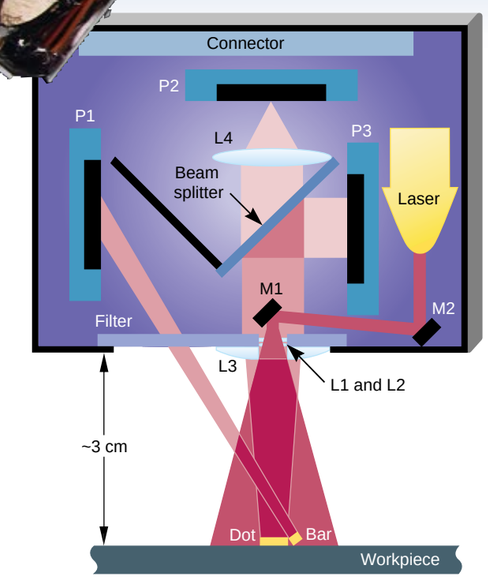


Photo of sensor with a quarter lying alongside. Below is an interior schematic view of sensor.



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.

For further information contact Charles Vann (510) 423-8201 (vann1@llnl.gov).

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.

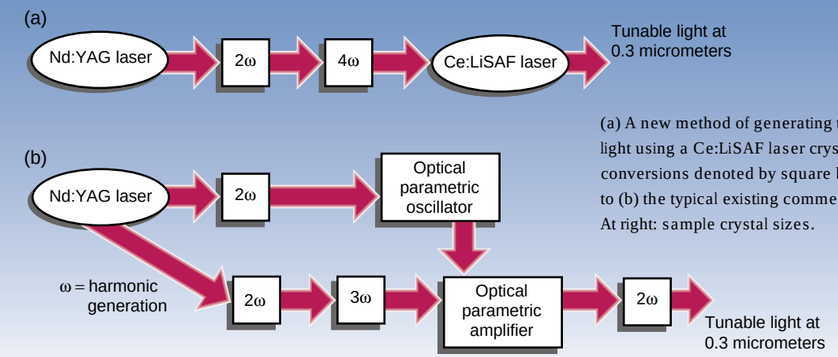
The new cerium laser crystal is a significant product for two reasons. First, it provides the ability to generate ultraviolet light directly, compared to previous methods that were far more complicated, less predictable, and worked only under restrictive conditions. Ultraviolet light is desirable for 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.

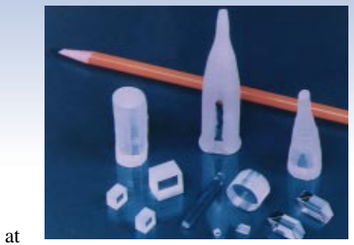
The second reason why the new crystal is significant is that it makes an ultraviolet solid-state laser system commercially feasible. Generating laser light is not simple because much of the energy put into the laser system ends up as heat. Yet light energy gain must be larger than the losses if lasing 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.

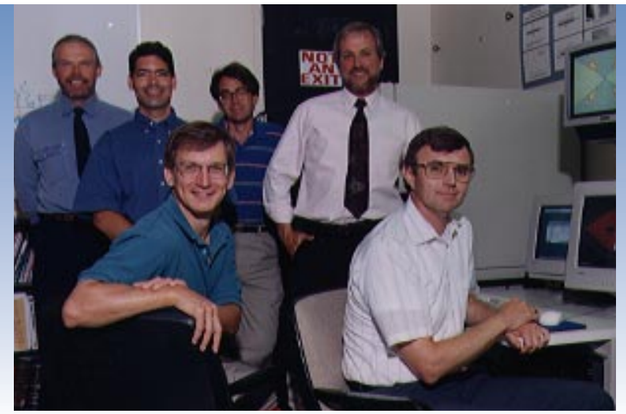
The U.S. Army is considering its use to monitor the presence of tryptophan, a common component of biological weapons. Another potential military use could be to secure wireless communications links between infantry units over short distances of approximately 1 kilometer on a battlefield. Because ultraviolet 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.

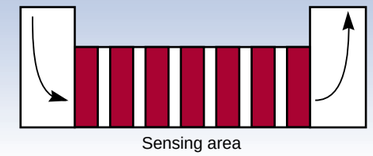
Key Words: Ce:LiSAF, cerium crystal, R&D 100 Award, tunable ultraviolet laser, solid-state laser.

For further information contact:
Chris Marshall (510) 422-9781 (cmarshall@llnl.gov).

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.)



Configuration of the CPP–GMR sensor.

"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.

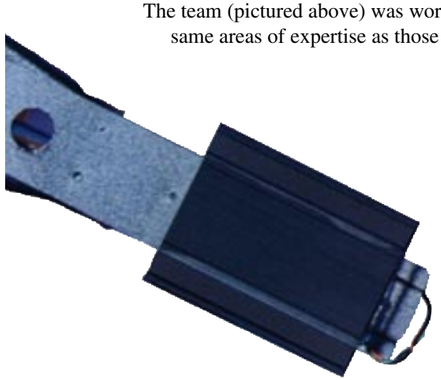
Magnetic sensors are a key component of the disk drive. They determine how much and how fast the disk drive can "read." Because computer users are constantly demanding higher density disk drives (with more memory in the same physical space), manufacturers must constantly push to make smaller and smaller 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.

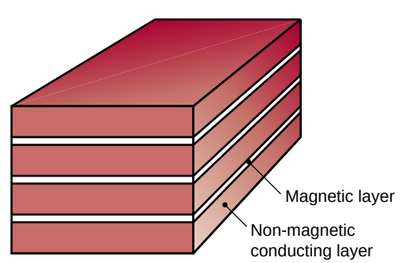
The team (pictured above) was working in some of the same areas of expertise as those in magnetic sensor research and development, and they became intrigued by the solutions that industry researchers were proposing for the magnetic sensor problem. They wondered what they might be able to do to help solve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

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.

For further information contact Andrew Hawryluk, (510) 422-5885 (hawryluk1@llnl.gov).

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.

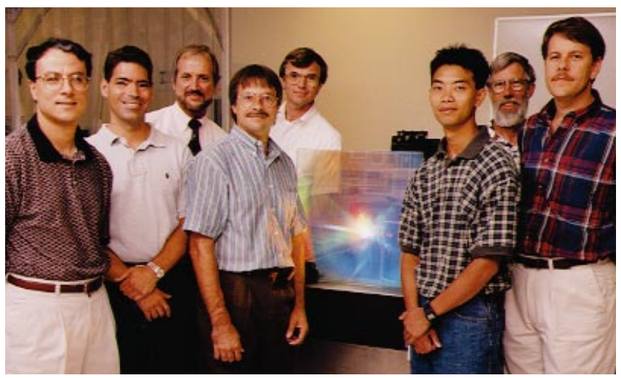
Switching on blocks of emitters that comprise a pixel in a given sequence achieves the same effect as changing a selected pixel in a liquid crystal display. What's more, FEDs produce high brightness over the full range of color, but could require only one-tenth to one-half the power of a conventional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

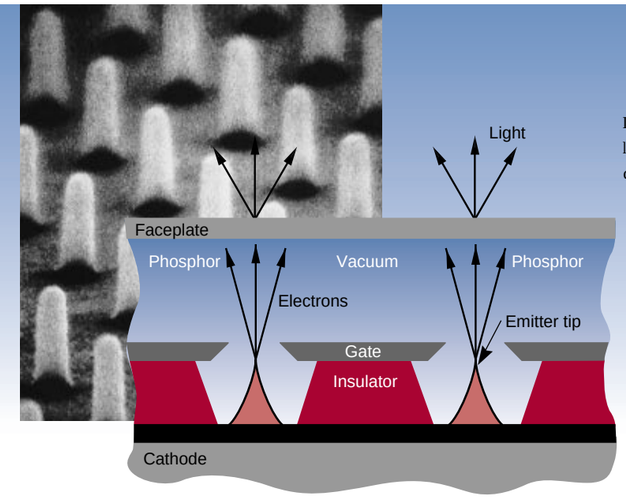
Citing U.S. firms' mediocre penetration into the critical flat-panel display market, the federal government formed the U.S. Display Consortium and assembled a White House Flat Panel Display Task Force. Both the consortium and the task force concluded that to develop a viable domestic flat-panel display 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.

For further information contact Michael Perry (510) 423-4915 (perry10@llnl.gov).

*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).

Assessing Humanity's Impact on Global Climate

Lawrence Livermore's Atmospheric Sciences Division is applying computation expertise—originally developed to simulate nuclear explosions—to the task of climate modeling. We also make use of Livermore expertise in atmospheric science that grew out of efforts to model fallout from nuclear testing. These model-building and simulation efforts in climate studies are synergistic with other Laboratory programs that depend on combining computing with information and communication management.

Major efforts are aimed toward understanding how the biosphere and oceans take up and remove carbon dioxide, what role pollutants from fossil fuels play in determining sulfate aerosol concentrations and the impact on climate, and to what degree climate naturally varies within the biosphere. In addition, we work to reduce systematic errors in the models in collaboration with researchers in LLNL's Program for Climate Model Diagnosis and Intercomparison.

■ *Contact:*
William Dannevik (510) 422-3132 (dannevik1@llnl.gov).

© 1996. The Regents of the University of California. All rights reserved. This document has been authored by the The Regents of the University of California under Contract No. W-7405-ENG-48 with the U.S. Government. To request permission to use any material contained in this document, please submit your request in writing to the Technical Information Department, Publication Services Group, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, or to our electronic mail address*report-orders@llnl.gov*.

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California and shall not be used for advertising or product endorsement purposes.

U.S. Government Printing Office: 1996/784-071-60002