Seeking Coherent Answers

Laser researchers are developing coherent-light solutions to a host of existing challenges

BY JANET RALOFF

Every year more and more lasers are sent from the research community to be used in commerce and industry. They are already employed reading prices off products crossing supermarket checkout counters, welding detached retinas, cutting through steel and shooting three-dimensional movies. The next wave of recruits may enrich uranium, broadcast messages through the ocean to converse with submarines, or reduce the "noise" in audio and optical recordings. What follows is a glimpse of the diversity in research programs attempting to generate such recruits.

MEDICINE

Lasers entered the surgical theater during the late 1960s. Their ability to direct intense beams of energy into tissue without requiring either mechanical or electrical contact eliminated much of the trauma—such as tissue charring — associated with previous attempts to treat medical problems with heat.

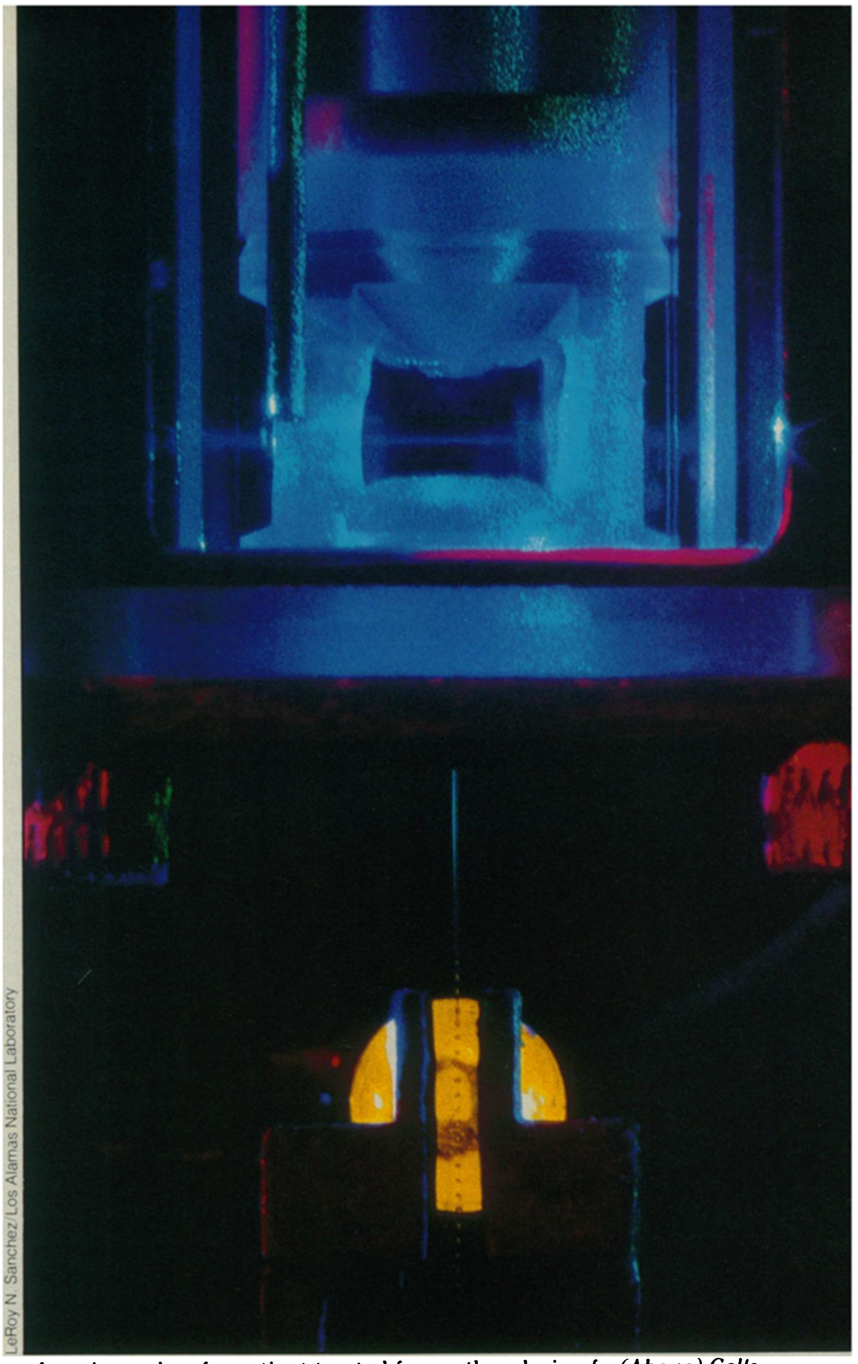
So that neither a bleeding body nor a laser had to be tilted radically for a lesion or tumor to make proper contact with the scalpel-like beam, most early efforts in laser surgery focused on external tissues. But laser optics and advances in optical fibers—those flexible, hair-thin glass rods — have changed that. Carried inside endoscopes (medical instruments for viewing interior organs and canals), optical fibers now permit the intense and powerful beams of modern lasers to be curved and moved throughout the body's internal cavities without jarring a laser system's fragile and precisely aligned components. And certain sophisticated laser systems permit beam-exit ports to virtually dance over a patient's body at the surgeon's command. This resulting freedom has encouraged surgeons to explore internal use of laser cauterization and vaporization.

Joseph H. Bellina of the Laser Research Foundation in New Orleans, for example, has been using carbon-dioxide (CO_2) lasers in a wide range of gynecological operations since 1974 (SN: 2/7/81, p. 90). In a paper he delivered in Washington recently at the Conference on Lasers and Electro-Optics (CLEO) Bellina presented preliminary results of a study involving 97 women who underwent fertility-enhancement laser microsurgery at F. Edward Hebert Hospital's Reproductive Biology Center in New Orleans. In 93 percent of the cases, surgery to open blocked or otherwise closed fallopian tubes proved successful. "Eliminating those cases in which the women decided to take contraceptives or were placed on prohibitive medical therapy . . . conception has occurred 16 times among 15 of 24 patients," he says. "This is approximately 50 percent of those patients who could anticipate pregnancy."

Samuel Rosemberg of Sinai Hospital of Detroit reported several firsts with clinical use of a 50-watt continuous-wave (CW) and rapid superpulse (RSP) CO_2 laser in urology. One case involved the complete healing after six weeks of a patient treated for erythroplasia of Queyrat, a penile lesion considered the earliest manifestation of penile cancer. In the past the disease has sometimes been treated with fulgaration (destruction of tissue using electrical sparks), irradiation and partial or complete amputation of the penis.

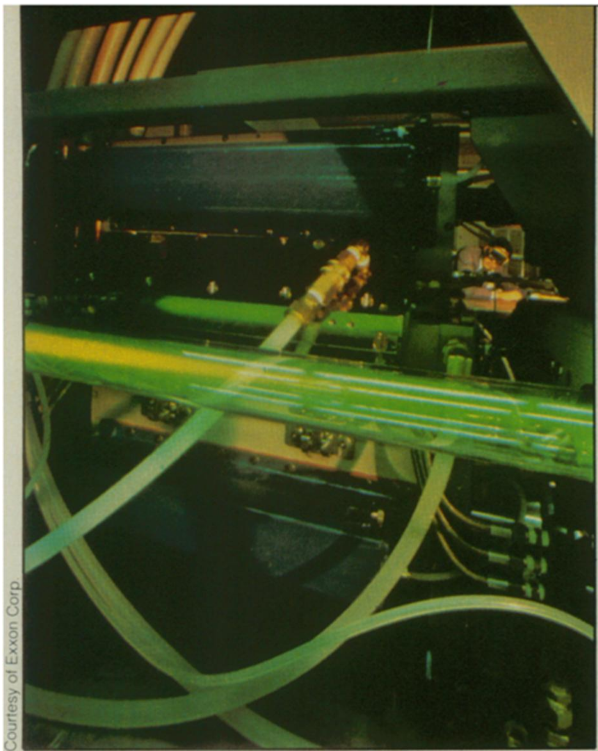
Rosemberg also reported eradication and the complete healing of a Bushke-Lowenstein tumor after 12 weeks. Both CW and RSP treatment resulted in eradication of urethral condylomata — soft, friable lesions, sometimes called venereal warts, and caused by a filterable virus — among 86.6 percent of the 22 patients (16 males, 6 females) treated in a single laser application.

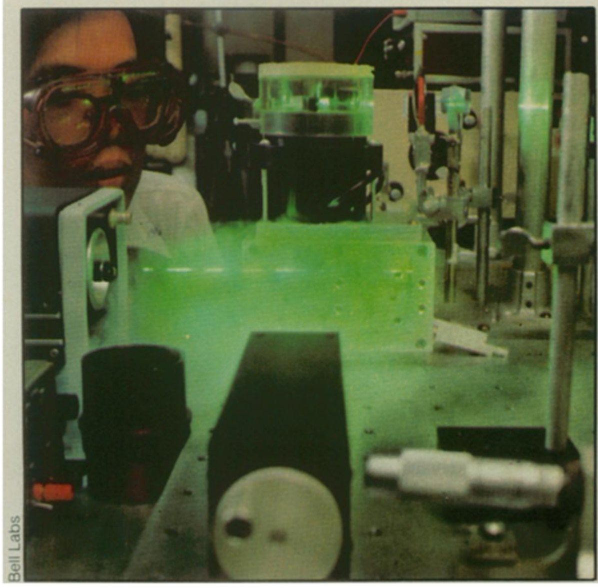
Richard Dwyer notes that lasers provide one of the safer ways to coagulate bleeding gastrointestinal ulcers. According to the University of California researcher at Harbor General Hospital in Torrance, "The success rate of the argon laser on selected patients is roughly 80 percent, and the success rate of the [neodymium: yttrium-aluminum-garnet laser] on unselected bleeding patients is 90 percent." What's more, endoscopic-laser surgery "can replace emergency surgery for . . . bleeding with elective surgery," Dwyer claims, adding that this procedure not only is safer for the patient, but also

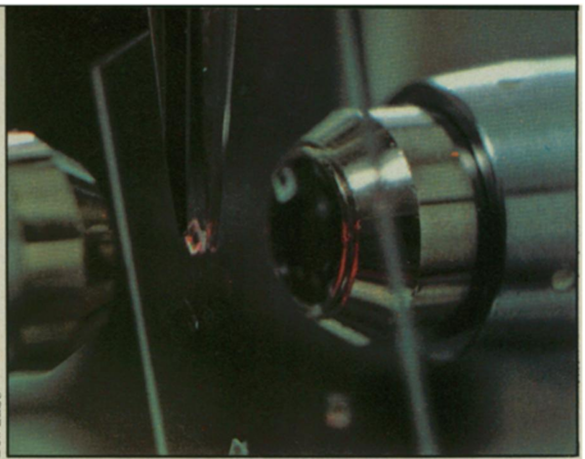


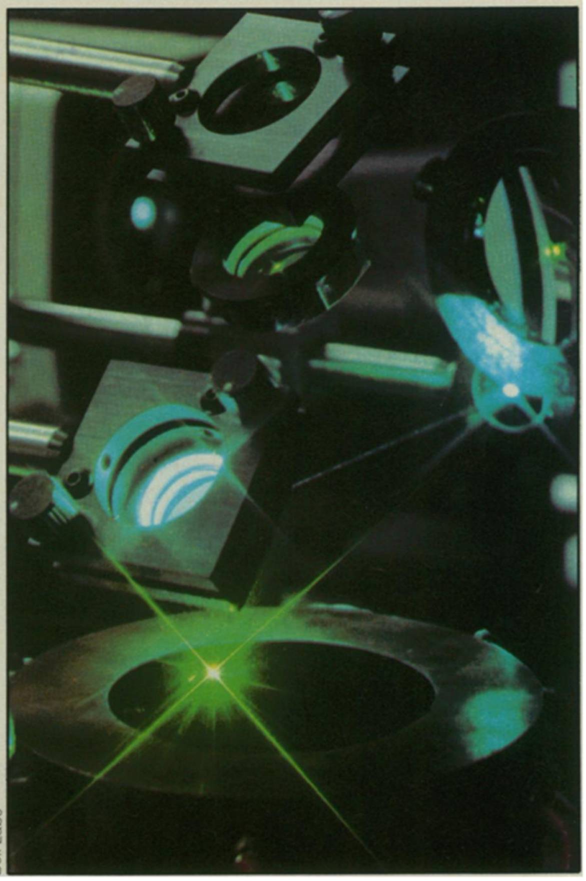
LeRoy N. Sanchez/Los Alamos National Laboratory

(Above) Cells passing through flow-cytometer chamber are illuminated with red and blue lasers. Strobed blue liquid stream of cells is seen exiting bottom of chamber. Exiting cells can be selectively removed by charging them electrically and then deflecting them from the flow.


Courtesy of Exxon Corp


Bell Labs


Bell Labs


Bell Labs

Clockwise from upper left: High-power laser (shown, left top), is used in atomic-vapor process to excite U-235 for separation from U-238. Small semiconductor laser (right top) sandwiched between micromirrors, near tweezers, is used to study production of picosecond pulses. Laser (right bottom) used in annealing to produce high-quality crystalline semiconductor layers less than 1 micron thick. Phonon laser (left bottom) is new diagnostic tool to study crystal flaws on atomic scale using ultrashort-wavelength phonons — acoustic vibrations with the wavelengths of X-rays — as they are transmitted through semiconductor samples.

reduces the hospital stay required, blood transfusions necessary and days of work lost by the patient.

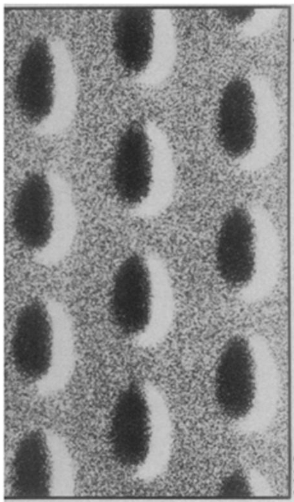
Perhaps even more impressive is use of lasers to photovaporize the endometrium (inner, mucous layer of the uterine wall) as an alternative to having a hysterectomy for women suffering from menorrhagia — excessive bleeding or prolonged menstruation. Terry Fuller at Sinai Hospital in Detroit noted that the treatment succeeded in reducing or eliminating menstrual flow in all but one of 55 women who underwent the experimental surgery. Endometrial biopsies 20 months after surgery confirmed that no serious inflammation and only minimal endometrial regrowth had occurred.

And for sleuthing tooth decay, lasers provide a simple and convenient tool to detect developing cavities, F. Sundström of the Karolinska Institute in Stockholm and H. Bjelkhagen of Sweden's Royal Institute of Technology reported at CLEO. Carious lesions in tooth enamel show up as dark spots when illuminated with blue light from an argon-ion laser. "Even initial pit and fissure lesions are clearly visible." And the procedure they developed makes it possible to spot these decay signs before they would otherwise be detectable with either visible light or ultraviolet fluorescence, they say.

DATA REPRODUCTION

Videodiscs promise to do for video what phonograph records did for sound — make prerecorded high-quality offerings available as affordable home entertainment. In commercial videodiscs today, images are recorded as a binary code spelled out in combinations of pits and spaces-without-pits. A tiny, focused laser beam burns these pits into a recording platter. To play back the images, a light passes over the disc. The presence or absence of pits triggers a photoelectric receptor to translate the encoded message into electrical signals which are eventually converted into a television picture.

Unfortunately, the laser generally does not produce clean-edged pits, says William Robbins of 3-M Co. "It is like thumping the tip of a baseball bat into a bed of partially set concrete: You get a neat hole, but the displaced concrete forms a ragged ledge around its top." In the microscale typical of video recording, these ledges appear enormous. And their nonuniformity frequently confuses the playback system, resulting in a poor "signal-to-noise" ratio, or static-like interference. What results is less-than-clear image reconstruction. However, we can usually tolerate such noise in optical recordings, Robbins says, because "our eyes and imagi-



Scanning-electron micrograph of cast, polymer replica of optical recording blisters. Each bubble is roughly 0.8 micrometer in diameter and 200 nanometers tall.

nations fill in occasional voids and our expectations subconsciously drop to match what we see."

Machines, though, lack the intellect to smooth out these rough edges — to tune out the noise. And that's what makes the recording of data on these same platters a potentially risky proposition. Data — such as numbers indicating bank-account transactions — can be recorded on blank discs as easily as video data. The precision of each binary digit contributes to the accuracy of each coded number or letter. So misreading just one bit could alter an important number, and radically change the meaning of a piece of data, such as a checking-account balance. But Robbins and colleagues at 3-M have created an alternative laser-recording process that they claim is essentially noise-free. Originally designed for production of high-quality digitally mastered audio and video recordings, the process will be used even more in the business-data industry, Robbins says.

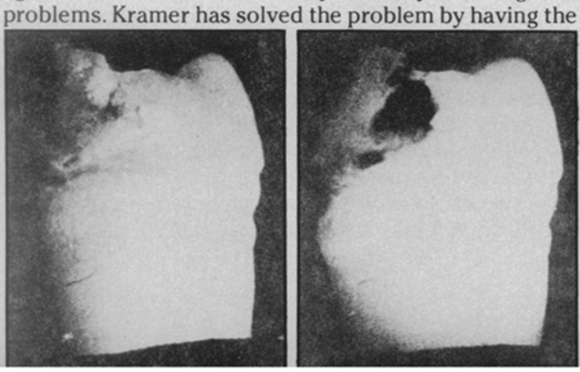
Instead of pitting a disc's surface, the 3-M process generates uniform submicron-size blisters. The recording medium consists of three layers that, depending on the materials used, can range from 60 to 400 billionths of a meter thick. The upper layer is a tough, thin film of optically absorbing refractory material. The next layer is generally transparent. A reflective metal film is on the bottom. All three are deposited on a substrate fitting the degree of flatness required by the laser recorder. A burst of laser energy heats a spot on the recording medium to temperatures of about 1,500°C to 2,000°C. Heat-induced outgassing of material in the middle layer causes a bubble of gas to raise a blister in the refractory surface. Blister formation makes the otherwise optically nonreflective upper surface now very reflective.

Blister size is easily controlled, uniform and small, permitting clear and dense recording. A line of 80 blisters, including flat spaces between them, is only as wide as a human hair is thick, so that a disk the size of a standard phonograph record could contain 10 billion blisters. Theoretically, the entire *Encyclopedia Britannica* could be recorded on one such disc. At 50 billionths of a second per blister, current reading and writing rates are rapid. And the disc's surface is so tough it can be copied much the way phonograph records are stamped out. Envisioned uses include the recording of computer programs in a way that resists unauthorized alteration and archival storage of business data.

The concept behind Charles Kramer's holographic beam deflector — or hologon — for laser scanners used in non-impact printers is less easy to envision but potentially at least as important. According to the physicist at Xerox Corp.'s Wilson Center for Technology, xerographic devices using laser printing could develop into a $10 billion industry by 1985. And holographic scanners could lower the cost of those printers.

The keys to Kramer's hologon are its four facets. Each is an identical transparent window on which a ridged pattern has been imprinted. When laser light passes through, each facet acts as an optical grate, diffracting light. A single, inexpensive doublet lens focuses the passing beam, and rotation of the grating facets causes the beam to scan in a focused point.

Previous hologon designs suffered from distorted images, due to bowed scans, and potentially disabling lens problems. Kramer has solved the problem by having the



Human tooth with large carious region in upper left corner: Viewed in normal light (left photo), in laser luminescence (right photo).

laser form a 45° angle to the hologon surface (see diagram) as it enters a grating, and a 45° angle to the opposite surface as it emerges from the grating. This angling results in a straight-line scan as the hologon revolves.

MILITARY COMMUNICATIONS

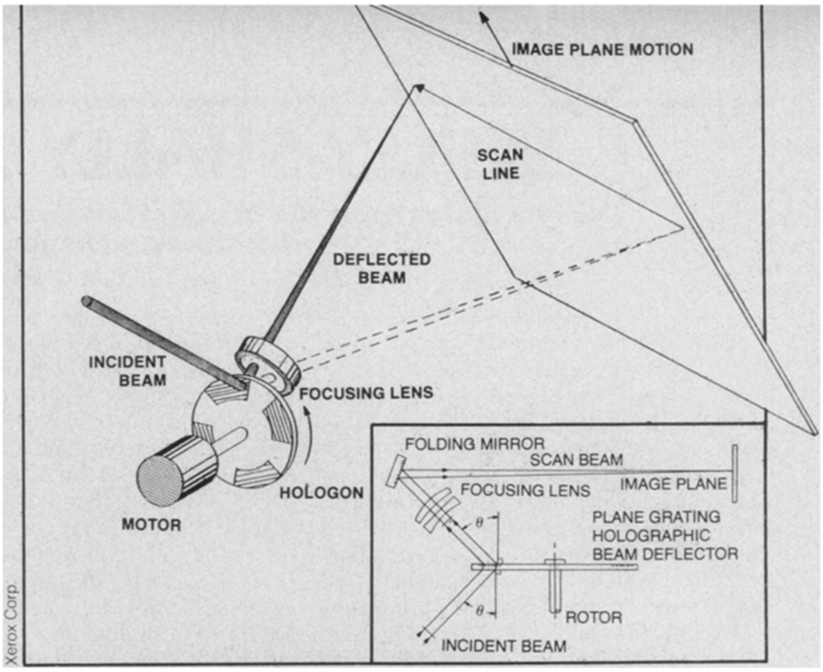
How do military leaders in Washington communicate directly with a submerged submarine hundreds of miles out at sea? They don't, today. Radio and conventional acoustic signals dissipate into useless garble after traveling a modest distance through water. And that presents a major problem for the Navy because a submarine risks revealing its location — a serious threat to its security — whenever it surfaces to receive or broadcast messages. One solution is to use messages coded in pulses of blue-green laser light, which can penetrate water without distortion.

Two schemes are currently under study. In one, land-based transmitters "talk" to a satellite via microwaves or another signal. The satellite's laser then relays a translated light signal to the sub. In the second scheme, a laser on the ground bounces beamed signals to subs via relay mirrors carried aboard satellites.

While neither system is without drawbacks, the Navy currently favors the satellite-based laser, according to Tom Shay of the Naval Ocean Systems Center in San Diego. The major reason, he says, is that the satellite laser requires a device producing only "on the order of 1 to 2 joules per pulse," whereas land-based laser transmitters must be much larger — perhaps a kilojoule per pulse. And the higher the laser's required power, the more costly and difficult it is to develop. More important, the ground-based laser would be so large that there are only a few places — "maybe half a dozen in the U.S.," Shay says — where it could be situated. And like proverbial sitting ducks, once found by an opposing military force, such a laser could easily be knocked out. Shay claims that because "satellites are smaller and always moving, they are harder to knock out." Their major disadvantage, he says, "is that there are no service technicians in space yet, so the satellite's laser has to last for five years. And that is a very stringent constraint." The Navy's other preliminary requirements for space-based lasers are that they fire 100 times a second, and operate with at least 1 percent efficiency.

Already there are two front-running candidates. Except for the required 5-year life, mercury-bromide ($HgBr_2$) lasers have achieved each of the Navy requirements. "But they have not yet been achieved in the same device," Shay notes. And since the first $HgBr_2$ laser was made only four years ago, no one yet knows whether it can operate for five years. The xenon-chloride laser, a close contender, is an ultraviolet-emitting device whose output has been "frequency shifted" using a high-temperature lead cell into the blue-green range. Whether or not either candidate survives, the Navy knows the concept is sound: In ongoing tests, lasers being flown aboard airplanes already talk to submarines.

The Air Force also has a space laser-communications program. Begun in 1969, its initial goal was to develop the capability of sending and receiving one billion bits of information each second between planes and ground bases. Because transmitters and receivers use optical elements such as prisms, mirrors and lenses, the plane-loaded laser required gimballed and motor-driven mirrors to maintain precise beam alignment. The hard part was to get two neodymium: yttrium-aluminum-garnet lasers — one on the ground, one on the plane, and each the size of three stacked pocket watches — to lock and transfer data. The system's feasibility was proved last December when videotape and live-video data were



(Above) Kramer's hologon overcomes a host of optical distortions that had been plaguing holographic imaging systems for laser-scanning xerographic printers. Laser-beam optics, shown in inset, describe how Kramer avoided the normally bowed line as characters were scanned across a flat paper page.

transmitted between a flying aircraft and a ground station at the White Sands Missile Range.

MATERIALS PROCESSING

Lasers have the ability to heat the near surface of a material, such as silicon, and to leave it in a molten state for a hundred billionth of a second. In the ultra-rapid cooling that follows, formerly jumbled atoms will line up into stable crystalline arrays, much the way orderly ice crystals form as water freezes. But by using *trillionth-of-a-second* pulses of laser energy, the surface of what formerly existed as a single crystal of silicon can be jumbled into an amorphous state. "The mechanism," explained N. Bloembergen of Harvard University in a CLEO presentation, "is melting of a crystalline layer with subsequent solidification so fast that the atoms literally do not have time to find a regular crystalline position."

How laser annealing—this surface alteration of materials first demonstrated by the Soviets in 1975—can be harnessed has been actively studied in the United States for five years. Already, the process is being used to selectively correct defects in semiconductor surfaces. But what may prove more important, notes Richard F. Wood of Oak Ridge National Laboratory, is that engineers at last have in their grasp a tool with which to fashion electronic materials "with tailor-made electrical properties."

URANIUM ENRICHMENT

One microscale process being contemplated for macroscale application is the isotope separation, or enrichment, of uranium using lasers. Of naturally occurring uranium species, the most important are U-235 and U-238 — usually found mixed in natural concentrations of 0.7 percent and more than 99 percent, respectively. Before the fissionable U-235 can be used to fuel commercial nuclear reactors, its concentration must be enriched from the 0.7 percent level to about 3 percent.

Today all uranium enrichment is carried out by a costly gaseous-diffusion process developed during World War II. Natural uranium is repetitively cycled through a process to extract U-235 from its sister isotopes. However, process wastes, known as "tails," typically contain roughly 0.2 percent U-235. If the U-235 concentration in tails could be economically reduced to 0.1 percent—either during or after primary enrichment processing—the nation's usable-uranium resource base would effectively be increased by 16 to 19 percent. And laser isotope separation is one concept being explored to reduce enrichment costs — currently running about $300 per pound of reactor fuel.

The atomic-vapor process takes advantage of small, isotopic differences in the electronic spectra of uranium atoms. After vaporizing uranium, the U-235 component is selectively excited and ionized using tunable lasers in the visible-light or ultraviolet-light regions. A classified electromagnetic method then removes the U-235 vapor. In an alternative scheme, uranium hexafluoride (UF_6) is supersonically expanded through a nozzle to reduce its internal temperature and to simplify the absorption spectrum of the gas. Molecules of the UF_6 are then exposed to laser radiation in the infrared and ultraviolet range, yielding enriched uranium as solid UF_5—separable from the gaseous UF_6. Components for experimental plants to test each process are under construction. Operation of both plants is slated to begin next year.

ANALYTICAL TOOLS

Modern chemical weapons — nerve agents — are colorless, odorless, tasteless and otherwise undetectable until the troops start reeling with respiratory and gastric complaints. But laser-detection of the toxic gases with a system under development at Los Alamos National Laboratory could provide the advance warning necessary to save front-line troops. It also could detect deadly residue absorbed by the surfaces of battlefield equipment.

The heart of the system is an inexpensive medium power neodymium: yttrium-aluminum-garnet laser whose light — delivered in 10-nanosecond pulses — is directed at air samples to be analyzed. The intense light, focused on a small volume, creates a plasma that reduces particulates and molecules to elemental ions. A monochronometer disperses the spectra, which are picked up by a photomultiplier to quantify readings of the spectra sought. Sulfur and chlorine, constituents of blistering agents, are easily identified. Similarly, phosphorus and fluorine — characteristic of nerve gases — could indicate the nature and quantity of these agents wafting across battlefields.

But the system also has civilian applications. In fact, it was first tested to measure airborne beryllium-dust levels in shops where the metal was machined into weapons components. It proved so effective that Los Alamos is now considering development of an on-line continuous monitor, perhaps using a laser aimed through a window at the end of a sampling tunnel near machines. And in field tests, the system was used to detect alkali metals—such as sodium and potassium — that could corrode turbine blades in an experimental coal gasifier.

Another sampling device pioneered at Los Alamos scans cells from the human body as they flow through it in single file — at a rate of 3,000 per second. Flow cytometers are able to measure cell size, DNA content, the presence of specific antibodies, permeability of cell membranes to particular molecules, the migration of specific receptors on a cell's surface, chemical-reaction rates inside cells and even the shapes and sizes of individual chromosomes. Most applications rely on measuring the fluorescence generated from dyes, used to tag or stain specific biological molecules within cells, passing through a laser beam. Cells are illuminated uniformly by the laser as they pass through the lower region of the cytometer's chamber (see p. 184), so the intensity and duration of fluorescence reflects the concentration, and in some devices the location, of the stained molecules in cells. And cell structure can be gauged by how the laser beam is scattered as a cell passes through it.

Computers have revolutionized the economy and productivity of American homes and businesses. The diversity of research capsuled here suggests that lasers may do the same in coming decades. □