Laser applications promise to revolutionize industry

Part II of an overview by Charles B. Stevens, of the capabilities of lasers to transform the civilian economy, 'spinning off' the Strategic Defense Initiative.

Summary of Part I: Through a combination of continuing advances in demonstrated laser capabilities in the inertial confinement fusion energy R&D program and a series of breakthroughs by the Strategic Defense Initiative program for developing defenses against nuclear-tipped missiles, laser capabilities have become even a little overripe for a broad-based revolution of industrial technology. The 1990s will be seen as the initiation of a second industrial revolution—if Americans have the courage and prescience to grasp this opportunity for economic revitalization and reindustrialization.

Lasers transform more incoherent forms of energy into coherent beams of light. These coherent beams of light can be readily and efficiently transmitted and focused through a wide variety of media over great distances. The laser beams can be easily focused to power densities trillions of times greater than industry's current utilization.

Part I discussed general applications of lasers today, and then took a closer look at semiconductor diode array lasers and tunable solid-state lasers. This week's installment concludes the survey of the major types of lasers available for industrial applications.

Fusion R&D leads to efficient high-power, short-wavelength solid-state lasers

The workhorse of the inertial confinement fusion research effort has been high-power solid-state lasers. These lasers have been developed from an output level of 1 joule at 1 billion watt power levels and a wavelength in the range of 1,000 nm in the early 1960s, to their present level of up to 100,000 joules at 100 trillion watt power levels and a wavelength in the range of 250 nm for the Lawrence Livermore National Laboratory NOVA glass laser system.

Despite this record level of advances in output characteristics, until recently, the solid-state laser was not considered a serious candidate for actual laser fusion power plants, because of its apparently inherent low operating efficiencies. While solid-state lasers were most readily scaled to the high powers and energies needed for crucial inertial confinement fusion laboratory experiments, they did not appear to have the characteristics needed for efficient, high-repetition-rate operation needed for actual power plants.

But the large R&D effort invested in solid-state lasers has generated technological breakthroughs, which today have greatly enhanced their potentials for both efficient and high-repetition-rate operation. And while these advances have not made them the leading candidate for laser fusion reactors, they have become a leading candidate for existing industrial applications at lower pulsed power levels. This is all the more true, since the realization of efficient methods of harmonic wavelength conversion permits the high-power, solid-state laser to reach shorter wavelengths in the ultraviolet range and thereby use the more efficient ablative shock coupling of laser light for materials processing.

Over the past few years in particular, technologies have been demonstrated for operating solid-state lasers efficiently at near-diffraction-limited levels. These technologies have led to new materials, laser components, and systems architectures that permit efficient operation at average power levels in the range of 100-10,000 watts.

Many of these improvements are being tested on the Livermore glass zigzag slab laser which is designed to operate at 150 joules per pulse at a repetition rate of 2 Hertz. This laser employs an injection-locked regenerative amplifier cavity architecture incorporating a phase conjugator. Last year, high storage efficiency within the lasing medium was demonstrated on this laser, utilizing LHG-5 glass. Using an optimum reflector design, spectrally tailored lamps, combined with a low-loss pump cavity and flashlamp pre-pulsing, researchers achieved as much as 7% of the flashlamp electrical energy's being stored in the glass lasing medium; that is, potentially giving a 7% operating efficiency as opposed to the fraction of a percent efficiency achieved with existing high-power glass lasers. Similar performance is expected from Nd:Cr:GSGG glass when this new material is fully developed.

The bottleneck in achieving high-quality beam output, efficient, high-repetition-rate operation with high-power glass lasers has been the problem of waste heat dissipation within the glass laser amplifying medium. Lawrence Livermore National Laboratory has demonstrated that, with the proper design for a glass slab geometry and cooling system, efficient, high-quality beam output can be attained.

A crucial aspect of this work is the ability to predict the optical effects of thermal stresses within the glass slabs. Recent experiments have verified two-dimensional computer codes, and major strides toward realizing full three-dimensional codes have been taken. Two amplifier test-beds are maintained. These permit verification of computer codes for various zigzag and gas-cooled slab architectures. Therefore, new laser material candidates can be evaluated against numerical simulation before incorporating the new laser components in a full-scale laser, where complex interactions with other laser components make understanding the system behavior difficult.

According to Livermore scientists, significant improvements in power, efficiency, and repetition rate can be expected with the incorporation of new lasing materials currently under development. The silicophosphate glass technology has matured with the development of Hoya HAP-3 glass. Large crystals of Nd:GGG and Nd:Cr:GSGG have been grown that have low absorption loss at the lasing wavelength. Theoretical methods for predicting the fracture of these materials under laser operating conditions were demonstrated experimentally. Furthermore, techniques for slab strengthening were extended to improve durability of the new laser materials as well. In addition to optimizing the slab design for beam quality, adaptive optics are being developed in conjunction with phase-conjugation techniques to correct residual beam aberrations.

The development of large-aperture crystals for harmonic transformation of NOVA's laser output from the infrared to the ultraviolet has provided the technology for similar high-average-power harmonic generation at projected efficiencies of better than 80% at average output power levels of greater than 1 billion watts. A data base covering more than 120 nonlinear materials has been developed for this effort.

Optical switches needed to realize high peak power harmonic conversion and Raman phase-conjugation shifting have also been developed.

In summary, the technology for efficient, high-repetition-rate, high-average-power (100-10,000 watt), solid-state lasers, operating at harmonically generated ultraviolet wavelengths, is being rapidly realized through the efforts of the Livermore laser program. This technology will be available for commercial applications soon.

Applications

Over the past two decades, tunable lasers have become an essential workhorse for scientific research. High-resolution and nonlinear spectroscopy, photochemistry, and nonlinear optics have been revolutionized as a result. The wider range of coverage offered by tunable solid-state systems permits research into entirely new atomic and molecular processes and transitions. The technological implications are immense.

For example, color-center lasers have revolutionized research on nonlinear phenomena in optical fibers. Substantive investigations of soliton generation and transport have recently emerged in exciting work carried out at Bell Labs in Murray Hill, New Jersey. Work by the group headed by Dr. L.F. Mollenauer has demonstrated low-loss transmission loss of soliton-shaped laser pulses through optical fibers.

This has opened up the prospect for decreasing telephone and data transmission costs by an order of magnitude. The decrease in transmission loss could increase the distance over which signals could be propagated without repeater stations, from the current maximum of about 500 kilometers utilized in ballistic missile field command, control, and communication systems, to over 7,000 kilometers. Alternatively, the data rate over existing optical fiber lines could be increased more than a thousandfold. And because soliton laser pulses can pass through each other with no effect, a single line could carry up to 100 separate channels simultaneously.

Further research on solitons could reveal how to utilize the soliton itself for compacting and later retrieving trillions of bits of data into and from a single soliton pulse. Potentially, this could lead to a trillionfold increase in the productivity of optical fiber communication networks.

Alternative studies have begun for utilizing solitons in fiber rings as data storage for optical computers. The horizons of opportunity have only just begun to come into view. This entire field of discovery only became experimentally accessible within the last few years with the advent of tunable solid state lasers in the 1,500 nm range.

Besides the growing use of optical fiber data-links, line-of-sight optical links are now beginning to be developed. Short-haul atmospheric data links are expected to become widespread in the near future as the laser technology becomes better established. A laser transmitter broadcasting to an optical receiver can provide a simple and inexpensive means of transmitting data across freeways, railroad rights-of-way, and other obstacles that complicate use of conventional transmission lines. Similar links are also needed for satellite-to-satellite communications, as already has been developed for various defense applications including communication with submarines.

For terrestrial links, lasers operating with a few watts of average power at wavelengths that are easily transmitted through the atmosphere are normally used, and GaAlAs diode laser arrays, with their small size and ease of modulation, appear quite suitable. Interestingly enough, the InGaAsP diode lasers operating at 1,550 nm, which were developed for optical fiber communication links, also have the ideal wavelength for good atmospheric transmission and lies beyond the 1,400 nm limit at which permissible eye exposure to laser radiation increases by several orders of magnitude. Combining InGaAsP diode laser technology with the diode array concept should result in a laser with good output power which penetrates the atmosphere well and is relatively safe.

In this context it should be noted that these atmospheric data links can also be extended to high power levels needed for energy transmission. The use of extremely reliable laser sensors makes this both safe and practical, as noted in the accompanying box on phase conjugation systems. Ironically, much of the research that went into the low-power-density solar energy R&D of the Carter administration days, could be applied to high-power-density worldwide laser transmission of energy. Mirrors orbiting in space could relay laser beams around the world and redirect and focus the beams onto a few square meters of photodiodes on each. This type of power transmission would not be practical in densely populated and developed areas, but would be most economic for remote regions and provide the means for rapid "electrification" of these areas. (These systems are also being investigated for possible use as a means of powering aircraft and earth-to-orbit rockets.)

Similar revolutions are to be expected as transition-metal-doped lasers are applied to ultrahigh-resolution and nonlinear spectroscopy. These applications are expected to take off as techniques developed for liquid dye-laser frequency stabilization are applied to solid-state lasers.

'Everything leaks'

Remote sensing currently tops the list for near-term applications of solid-state tunable lasers. Both NASA and the military are achieving rapid advances in this revolutionary field. The basic principle is that "everything leaks." That is, all objects—even solid ones—emit trace vapors of the molecules out of which they are made. Even the rapid advances in existing multi-spectral, passive sensing with existing satellites only hints at what the future holds for active sensing with differential absorption *lidar*—laser radar.

For example, much to the surprise and chagrin of the superpowers, scientists from third countries demonstrated that it was possible to transform raw civilian satellite sensing data into pictures with much greater resolution and discrimination through computer enhancement of multi-spectral data.

With the placement of tunable lasers in space, it will be possible to tune in on particular molecular transitions and resonance and thereby detect the existence of trace elements—even from space. Because of the fortuitous coincidence between some molecules and the line tunable CO_2 lasers, already deployed in satellites, some experience with this type of remote sensing has already been demonstrated. But the number of different molecules detectable with the CO_2 laser is limited and the lack of continuous tunability prevents measurement of the absorption lineshape. Lineshape analysis can provide information on atmospheric pressure and temperature.

The simplest remote-sensing technique utilizes measurements of transmission as a function of wavelength over a given path. This can be done by either placing a detector at one end of the path, reflecting the laser with a cooperative target, such as a retroreflector, or by reflecting energy from a diffuse target, such as a hillside. In cases where reflection is employed the technique is called differential absorption lidar (DIAL).

A more advanced system being developed by the SDI involves the detection of back-scattered laser energy from aerosols in the atmosphere. This method requires the use of an energetic, pulsed laser for reasonable ranges and has the advantage of yielding range-resolved data.

Both space-based and terrestrial applications of these ad-

Lasers with perfect aim

Historically, it is often a conceptually simple device that triggers a technological revolution. This was the case with the proverbial light bulb and more recently with the transistor and microchip. This same kind of development is currently unfolding in the field of lasers, with the realization of phase-conjugate mirrors and processing systems. Until the recent development of phase-conjugation, obtaining the optimum, distortion-free output for a coherent laser beam represented the most painstaking and difficult of problems. But with phase-conjugation it is now possible, for the first time, to aim and eliminate distortion from laser beams instantaneously, automatically, perfectly, and without the need for cumbersome machinery.

All of this is possible because phase-conjugation remarkably permits the reversal of time. Imagine that we film the following series of events. A rock is thrown into a pool of water. A series of circular wavefronts is formed and heads toward the banks of the pool. Waves already present in the pool distort the circular wavefronts. The irregularities of the pool bank further distort the wavefront. And eventually, after several reflections off the sides of the pool, all order is lost from the originally circular wavefronts. Now run the film backward. The distorted waves will reorder themselves and eventually flow back to the original circular wavefronts. This "running" film backward is phase-conjugation.

In the case of phase-conjugated mirrors this means that any bit of incoming light is reflected directly back to its source. This is analogous to a wall that always returns a ball to the thrower no matter what the angle of the throw.

Phase-conjugation makes aiming lasers quite easy. For example, scientists have developed what is called four-wave-mixing phase-conjugation systems for aiming lasers. All that's required is that the target be illuminated with a low-power laser beam. This indicator beam can come from any direction, but it will reflect in all directions. A tiny bit of it will therefore bounce toward the phase-conjugation system. Left to itself, it will hit the phase-conjugate mirror and bounce right back to the target, covering the distance at the speed of light. But if there is a laser-amplification chamber between the target and the phase-conjugate mirror, the beam will return vastly intensified.

The implications are enormous. The phase-conjugate mirror can aim a defensive laser beam at a speeding missile, maintaining focus despite pockets of turbulence in the atmosphere or irregularities in the trajectory of the missile. It could guarantee the precise convergence of multiple lasers on a single target. This is already being done in laser fusion research. It could align a beam carrying energy from a space-based orbiting power plant to a receiving antenna on Earth, or on an airplane, without any danger of the beam's wandering. It can allow light waves to carry signals through the air or through a length of fiber-optic cable without distortion-induced loss of information. And it could allow lasers to etch tiny circuits on the surfaces of silicon chips without the errors caused by the minute imperfections that occur in focusing lenses.

There are two basic types of phase-conjugate systems: In one, the triggering lasers operate at wavelengths unrelated to the light that will be reflected. In the second, they *are* the light that will be reflected.

The first, the four-wave-mixing PCM consists of a plate of clear plastic or crystalline material. Twin activating beams are trained on the plate. Where they meet, there are regions where individual light waves overlap, producing tiny hot spots. It is the hot spots—not any property of the plate itself—that do the reflecting. Any clear material, therefore, can be used.

The second type works on a principle called Brillouin scattering. A liquid or gas is confined in a clear tube. When struck by an incoming laser beam, the fluid reacts by forming a minute pressure wave. And the shape of the wave, inevitably, is just right for reflecting the beam back on its original path. Again, the type of liquid used doesn't matter.

vanced lidar sensing systems have immense implications for understanding and controlling all types of natural and industrial processes. Tunable solid-state lasers offer the best combination of high reliability and relatively high efficiency with long operational lifetimes required for satellite-based remote sensing.

Various space-based systems have been proposed. One program would place a system on the Space Station. A second would use an unmanned satellite, the Earth Observing Satellite (EOS) project. Both would use passive and active sensing techniques. Measurements utilizing DIAL (differential absorption lidar) would monitor atmospheric chemistry and meteorological conditions.

Among the potential applications in industry for laser-based remote sensing are on-line monitoring of plant emissions for pollution control, detection of potentially harmful levels of gases in environments such as gas-handling facilities or coal mines, and real-time sensing of parameters in a production line for process control.

Excimers

Before 1976 there were few really good lasers in the ultraviolet wavelength range. Argon ion lasers, frequency-tripled or quadrupled Nd:YAG lasers, and nitrogen lasers—all capable of few watts of average power at selected wavelengths between 250 and 350 nm and overall efficiencies of a few tenths of a percent—were commercially available. All of these systems had size and cost problems associated with low efficiency, and high average power in the ultraviolet was difficult to achieve. In 1975 Setser and his colleagues at Kansas State University demonstrated that rare gas atoms in metastable excited states could react with halogen-bearing molecules to form diatomic rare gas halides in a bound excited state—in other words to form an excimer. Decay of these excimer molecules to a weakly bound or unbound ground state was accompanied by emission of an ultraviolet photon. Later research showed that rare gas halide excimers can also be formed through rare gas-halogen ionic reactions and that they can be produced with relatively high efficiency when a suitable gas mixture is subjected to electron impact excitation.

The excimer is a particularly interesting laser since the very short lifetime of the ground state almost ensures population inversion and hence optical gain whenever the excited molecule is formed. This was demonstrated experimentally by 1975 with laser action based on the bound-free transitions of the XeBr, XeF, XeCl, and KrF excimers. These lasers utilized electron beam irradiation of rare gas-halogen mixtures to produce coherent output at 282, 351, 308, and 249 nm. Similar lasers utilizing transitions in ArF (193 nm) and KrCl (222 nm) were demonstrated, and it was shown that they could also be excited by creating a self-sustained electrical discharge in the laser gas mixture.

The optimal operation is generally achieved when a composition of the excimer laser gas mixture of a few tenths of a percent halogen donor (NF_3, HCl, F_2, and so on), a few percent active rare gas species (Xe, Kr, or Ar), and a large percentage of a second rare gas which is used as a buffer. Total operating pressures usually lie in the range of 1 to 5 atmospheres. Self-sustained discharge excitation of the laser is desirable for most applications because of the greater simplicity and component reliability associated with that approach, but it is difficult to produce uniform discharges of long duration in gas mixtures of this type. Onset of discharge inhomogeneities typically limits laser pulse durations to a few tens of nanoseconds in discharge-excited devices, although pulses of 1 microsecond have been produced with electron beam excitation. Dissociation of the halogen donor imposes an upper limit of about one microsecond on the duration of pulses from any rare gas halide device.

Recent advances in the fusion and SDI research programs have greatly improved the prospects for efficient and maintenance-free excimer lasers despite the problems of having to utilize reactive gas mixtures, intense ultraviolet radiation damage to optical components, and the need for fast, repetitive, high-power excitation of the medium—which requires very fast, higly reliable switches.

Because of the unique manner in which ultraviolet light interacts with matter, excimer lasers are currently finding greater application to materials processing. Most significantly excimer lasers can remove material by ablation rather than through thermal processes such as melting, evaporation, or vaporization. This ablative shock removal of materials permits a much higher degree of precision than can be attained with other types of lasers.

At first it was believed that the interaction of ultraviolet radiation with organic materials was primarily photochemical in nature—that is, that absorption of a single excimer-laser photon by a polymer molecule leads directly to dissociation, provided that the photon energy is greater than the bond energy. Therefore, when a polymeric material is irradiated by an excimer laser, many chemical bonds are broken. This produces molecular products which have a much greater specific volume than the original polymer. This, combined with the excess energy of the ultraviolet photon, generates the shock ablation removal of material.

But other research has shown that thermal and collective effects also play a major role in the dynamics of shock ablation with excimer lasers. For example, it has been shown that for power densities below a certain level, for a given material, the interaction is primarily thermal. Above the power density threshold, the interaction becomes photochemical and therefore more efficient in terms of ablation. More recently, it has been shown that multiphoton processes can also play a role in the ablation process.

Research is continuing to uncover further complexities in the ultraviolet light driven ablation process. But despite this, it has been shown that material is removed layer-by-layer on a pulse-by-pulse basis. And each layer is about .3 microns thick. This permits fine control of the depth of cut that is obtained. Furthermore, most of the laser pulse energy is utilized in bond breaking and creating the ablative shock. Therefore, very little laser energy is deposited in the remaining material. This means that the physical mechanism of ablation differs from that of ordinary thermal mechanisms seen with longer wavelength laser processing.

In general the chief features of the excimer-driven ablation process are: 1) it removes material with extremely high precision and excellent edge definition; 2) absence of any significant charring or burning of surrounding material; 3) minimal heating or the remaining substrate and therefore virtually no distortion of the bulk material; and 4) the use of mask imaging processing of entire surface instead of spot focusing, piecemeal processing of the workpiece.

This last characteristic is crucial for efficient production of defect-free electronic and microchip components. The mask is generally made of a metal that has a much higher fluence threshold for ablation than the material being processed. Thus, the mask remains undamaged while the workpiece is etched. It is the use of the mask that allows one to simultaneously process an array of holes or a comb of slots. For repetitive patterns, the parallel processing capabilities of the excimer laser, together with the mask imaging technique, allows a much faster throughput than the serial approach utilized with CO_2 and Nd:YAG lasers, which generally can only drill one hole at a time. Therefore, with the excimer processing rates are measured in terms of area instead of the more conventional linear cutting speed.

Excimers are also capable of more readily removing selected materials from an underlying substrate. In principle, the CO_2 and Nd:YAG lasers (reviewed in Part I of this article) can also do this, but in practice, because of the thermal nature of the interaction at these longer wavelengths, considerable disruption of the remaining substrate occurs. With excimer lasers on the other hand, the absorption of energy occurs within a localized region near the surface of the irradiated material, and very little thermal diffusion occurs before the material ablates. Therefore, the exposed material can be removed with the underlying substrate remaining virtually untouched.

Finally, the ablated material is in the form of solid black soot and gaseous etch products consisting of CO_2, CO, and H_2O. The black soot—carbonized material—can be easily removed from the workpiece and therefore leaving the laser machined features clean and ready for subsequent processing.

Applications

In general the excimer laser is revolutionizing the processing of materials ranging from polymers, semiconductors, metals through to glass. The most significant developments have occurred in: 1) the processing of free-standing polymer films; 2) selective removal of polymer films from metal substrates; and 3) selective removal of thin metal films from nonmetallic substrates.

CO_2 lasers are currently the main workhorses for cutting and drilling polymers. But the thermal cutting action of these lasers limits the minimum size of hole that can be produced. There is also a limit on the density of holes that can be produced. The ablative nature of the excimer virtually eliminates the heating of the affected zone and permits very precise drilling of small-diameter holes (less than 100 microns) in thin materials at spacings not much greater than the hole diameter. Also, because of the non-thermal nature of the ablative process, a large number of holes can be drilled at one time with a mask.

In general organic materials such as polymer films require excimer laser energy densities on the order of 100 millijoules per square centimeter for their removal. Metal films require an order of magnitude greater fluence—one joule per square centimeter before ablation takes place. This vast difference can be utilized to permit precise removal of thin films such as polymer films, adhesives, and photoresists from metallic substrates.

Alternatively, the excimer is also utilized to remove thin metal films from polymer and glass substrates. In this case when the excimer laser pulse irradiates the thin metal film, the bulk of the laser energy is absorbed in the metal film leading to localized melting. But, some of the excimer laser light penetrates to the metal-substrate interface and produces a pressure build-up at this interface. This pressure at the interface derives from the decomposition of a thin layer of the substrate and/or degassing in the case of glass substrates. The pressure build-up explosively removes the molten metal film. This technique can also utilize masks to produce complex patterns in single pass processing.

Excimer lasers are best suited for applications that require the removal of relatively small amounts of material with a high degree of precision and can therefore be combined with "thermal" lasers, such as CO_2 and Nd:YAG which would carry out the rough cutting—greater than several millimeters. The non-thermal cutting action due to excimer driven shock ablation makes them particularly attractive for applications where side effects of conventional thermal processing, such as charring and melting, are particularly deleterious.