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Some Emerging Applications of Lasers

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Basic research conducted over the past two decades has resulted in the accumulation of a vast amount of information relevant to laser applications. We are also witnessing the maturation of several areas of laser device technology (*1*), and a number of high-quality laser systems can now be purchased off-the-shelf. The improved availability of laser hardware, together with a large library of information on laser technology and laser-material interactions, creates an atmosphere that is conducive to the development of new and innovative applications of lasers.

Summary. New laser applications are emerging in almost every field of science. Many of them show both a high degree of technical sophistication and broad practical utility. The progress being made is illustrated by specific applications in three areas: laser microchemistry, optical disk data storage, and remote sensing.

In the medical area, the use of lasers in treating ulcers, skin diseases, and tumors and as surgical tools is becoming well established (*2*). Microsurgical operations on single cells have been demonstrated (*3*), and even the area of acupuncture has felt the impact of new laser technology (*4*). Lasers are used in fiber optic systems to achieve high data rate communications (*5*), and new fiber optic sensors with laser sources are capable of very sensitive measurement of pressure, temperature, acceleration, rotation, strain, and electric and magnetic fields (*6*). The potential utility of very high energy lasers in fusion energy sources has been documented (*7*). Short-pulse laser sources have been constructed which emit optical pulses less than 10^{-13} second in duration (*8*). These devices allow exploration of new temporal realms. New applications of lasers in cutting, drilling, welding, and marking solid materials are appearing almost daily, and laser "job shops" are springing up in response to a demand for laser machining operations. Military applications of lasers have shown an impressive rate of growth, and defense agencies are beginning to reap substantial returns on early research investments as laser technology contributes new capabilities in ranging and target designation. Future applications in communications and directed energy weapons systems are also possible.

Many of these application areas have been discussed in a number of excellent review articles (*9*). An idea of the ingenuity involved in some of the new applications of lasers and a sense of their potential in technology and commerce can be gleaned, however, by considering a few specific areas in which rapid progress is evident. Three examples from the areas of photochemistry, advanced instrumentation, and information storage are selected for discussion in this article and are presented with emphasis on the fact that these are but a few of many.

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Laser Microchemistry at Surfaces

The capability of fabricating structures on scales as small as 1 micrometer is central to progress toward increased complexity and simultaneous miniaturization of electrical, optical, and mechanical systems. Microstructure engineering has profited greatly from efforts in the semiconductor industry through which microfabrication at planar semiconductor surfaces has been developed into a highly evolved technology. Semiconductor processing is based on sequential application of masking processes that control material deposition and removal operations with high spatial resolution. Although those processes are clearly quite suitable for large-volume production of identical planar devices, they are not well suited to operations on nonplanar surfaces or to situations where flexibility is required in the control of surface composition and geometry.

Laser microchemistry offers a number of new methods for altering the morphology of a solid surface with high spatial resolution. The spatial coherence of laser radiation is essential to the success of these processes since it allows confinement of the reaction region to a very small volume. Although a number of variations have been explored, the experimental configurations are usually similar to those sketched in Fig. 1. The substrate to be processed is immersed in an atmosphere of gaseous reactants in a closed cell. Laser radiation enters the cell through a transparent window and is focused on or near the surface of the substrate by an external lens. The laser beam either photodissociates appropriate parent molecules to produce atoms which are deposited on or react with the surface, or it heats the surface in a small, well-localized region to temperatures at which chemical reaction of the surface with molecular species in the surrounding atmosphere occurs. Of the two approaches, that based on photodissociation has been explored more extensively.

In the photolytic approach to surface microchemistry (Fig. 1a) localization of the reaction is influenced by the size of the focal spot near the surface, the lifetime of the photolytic products, molecu-

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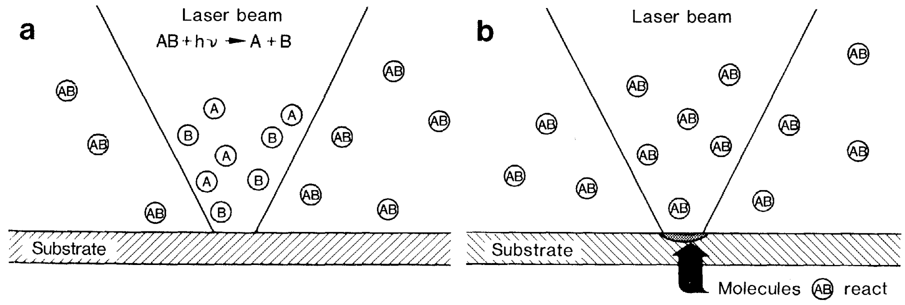


Fig. 1. (a) Microchemistry by laser photolysis. Free atoms produced through photodissociation of molecule AB diffuse to the substrate surface, where they react or are deposited. (b) Pyrolytic approach to microchemistry. Gas phase molecules react at a small laser-heated spot on the substrate surface.

lar diffusion rates, and the probability that the photolytic product will interact with the nearby surface. Resolution is enhanced by using inert buffer gases and quenching compounds to ensure that a reactive atom either interacts with the solid surface or is removed through reaction in the gas phase before it diffuses out of the volume illuminated by the laser.

With the pyrolytic or surface heating method (Fig. 1b), spatial resolution is a direct function of the size of the laser-heated spot on the substrate surface. This, in turn, is a function of the thermal characteristics of the substrate, the diameter of the laser beam at the surface, and the temporal characteristics of the laser radiation. By using a pulsed laser source with a pulse duration that is short relative to the thermal time constants of the heated volume, high resolution can be achieved.

In both the photolytic and pyrolytic approaches, spatial resolution usually can be increased to limits imposed by the finite dimensions of the optical beam. Since the minimum focal spot size associated with a coherent optical beam is proportional to wavelength, processes in which visible or ultraviolet lasers are used generally are capable of higher resolution than those with infrared sources.

Material deposition. Several groups have investigated deposition reactions appropriate for laser microchemistry, and many metals, semiconductors, refractory materials, and insulators have been successfully deposited on a variety of substrates with high spatial resolution. Deposition of cadmium, tin, aluminum, zinc, gallium, and germanium by photolysis of metal-alkyl compounds has been demonstrated at the Massachusetts Institute of Technology's Lincoln Laboratory (*10*) (see Fig. 2). In these studies a laser source, operating at a wavelength of 275 nanometers, was used to dissociate metal-alkyl molecules and produce a supersaturated metal vapor near the substrate surface. The laser also dissociates adsorbed metal-alkyl molecules on the substrate surface to produce small metal atom clusters, which act as nucleation centers and increase the sticking coefficient for metal atoms impinging on the surface from the surrounding gas. Since the probability of metal atom sticking to a clean ceramic substrate can be surprisingly low (10^{-4} to 10^{-5}), formation of these clusters strongly influences the initial stage of film growth and can be an important factor in achieving highly localized deposition.

In similar experiments researchers at Colorado State University (*11*) have demonstrated the deposition of chromium, molybdenum, and tungsten by laser photolysis. In this work, a 260-nm ultraviolet laser was used to dissociate metal hexacarbonyls to produce spatially localized deposition of these refractory compounds.

Although quartz or semiconductor substrates have been used in most photolytic deposition studies, the optical and chemical properties of the substrate do not play a major role in the deposition process. It is, however, necessary to match the laser wavelength to specific absorption bands of the parent molecular reactants. When the pyrolytic approach, based on laser surface heating, is used, optical and thermal properties of the substrate assume greater importance while less significance is attached to the optical properties of the gaseous reactants.

To date, most studies of pyrolytic deposition have emphasized adaptation of well-developed chemical vapor deposition processes which involve chemical reaction of vapor phase molecules at a heated substrate surface. These processes have been used predominately for growth of thin films and coating of large surface areas. Use of a laser to selectively process a small portion of a substrate surface is a natural and powerful extension of this technology.

Chemical vapor deposition is a stan-

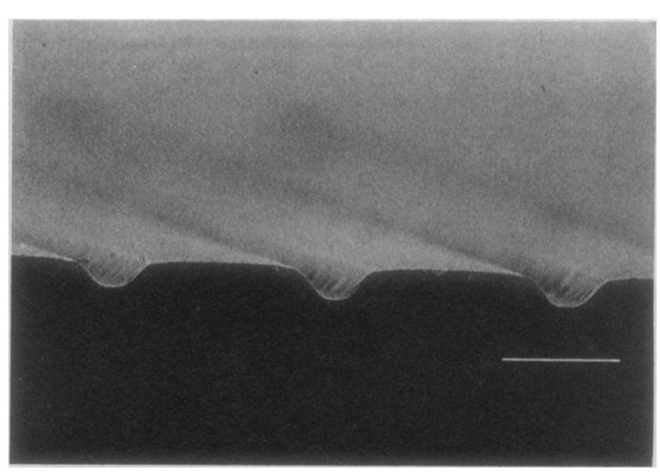
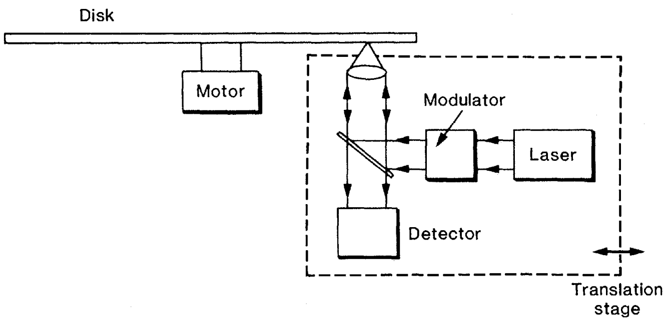


Fig. 2 (left). Metallic lines drawn by translating a silicon substrate during laser-controlled photolytic deposition of zinc. Width of the lines is approximately 0.7 μm. Fig. 3 (right). Grooves etched in silicon by translating the substrate during laser-controlled reaction of chlorine at the surface. The width of each groove is approximately equal to the laser focal spot diameter. Scale bar, 10 μm. [Photographs provided by D. J. Ehrlich, Lincoln Laboratory]



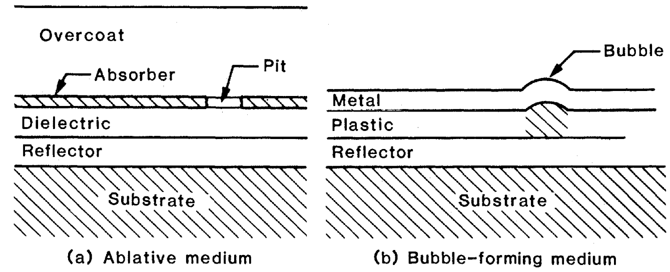


Fig. 4 (left). Basic configuration of an optical disk data storage system. A beam from the laser source is focused to a diffraction-limited spot on the surface of the spinning disk. Information is written onto the disk by modulating the intensity of the beam so that it produces sequences of alternately high and low reflectivity in circular tracks. Data are read from the disk by using a continuous, low-intensity beam to detect these reflectivity variations. Fig. 5 (right). Examples of multilayer optical disk media. (a) A multilayer medium on which data is written by ablation of pits in the absorbing layer. (b) A bubble-forming medium on which information is encoded by laser deformation of a thermoplastic layer beneath a partially reflecting refractory metal overcoat.

dard process in semiconductor device fabrication, and several experiments have explored localized deposition of silicon on ceramic and semiconductor substrates by pyrolytic decomposition of silane (SiH_4) or reduction of $SiCl_4$ by hydrogen at a tiny heated area on a substrate surface (*12, 13*). In other experiments, carried out at the University of Southern California, pyrolytic decomposition of nickel carbonyl has been used to achieve laser-induced deposition of nickel (*14*). And in a demonstration of the three-dimensional capabilities of microfabrication, a European research group has fabricated graphite columns only tens of micrometers in diameter but hundreds of micrometers high (*15*). These carbon deposition experiments were performed by pyrolytic decomposition of C_2H_4 on planar ceramic substrates or tungsten rods.

Material removal. If a laser can be used to initiate chemical reactions which result in deposition of material at a surface, one might expect other reactions to be possible which would result in material removal from a surface. Although only preliminary studies have been conducted in this area, the feasibility of laser microchemistry for material removal has been demonstrated. Experiments to date have focused on high-resolution etching of Si, GaAs, and InP semiconductor surfaces, although it seems likely that virtually any substrate material can be processed with a suitable combination of laser source and gaseous reactants. In experiments at Lincoln Laboratory (*16*), laser photolysis of halides such as CH_3Br, CF_3I, Cl_2, and HCl has been used to create a highly localized concentration of halogen atoms. These very reactive atoms diffuse to the solid substrate, react with its surface, and form gaseous products, which then diffuse away. In some situations, the laser intensity is high enough to produce local heating of the substrate, which accelerates the etching process. At the highest laser intensities thermally induced reactions appear to dominate the photolytically based ones.

In experiments on silicon etching with Cl_2, using several watts of blue-green argon ion laser radiation, etch rates greater than 6 μm per second were observed. As shown in Fig. 3, the laser could be used to "write" grooves of width approximately equal to the diameter of the laser focal spot (*17*). The laser could be similarly used to etch holes 10 to 50 μm in diameter completely through 250-μm silicon wafers.

Alloying and doping. In addition to material deposition and removal, laser microchemistry can be used to alloy or diffusively mix two solids on microscopic spatial scales. These operations are extremely important in the semiconductor industry and add a new dimension to microfabrication technology.

To achieve rapid diffusion of adsorbed species into the bulk of a solid or liquid phase mixing in a region near the surface, it is essential that the surface be raised to temperatures near the melting point. It is also desirable that an adequate concentration of the species of interest be maintained on the surface during these operations. By combining some of the concepts outlined above, lasers can be used both to photolytically generate free atoms, which are then adsorbed on a surface, and to locally heat the surface to the temperatures required for incorporation of these atoms into the bulk of the solid through diffusion or liquid phase mixing.

It is sometimes possible to use a single laser to produce both gas phase photolysis and surface heating. For example, solar cells have been fabricated by using an ultraviolet laser to photodissociate trimethylboron, $B(CH_3)_3$, over a silicon surface (*18*). The laser also heats the surface so that the boron atoms adsorbed on the surface after the photolytic step rapidly diffuse into the bulk of the material. After irradiation, the silicon is heavily doped with boron near the surface, and the p-n junction thus formed functions efficiently as a photovoltaic solar cell.

It may also be advantageous to use two lasers of different wavelengths to separately achieve photolysis and heating. In investigations of aluminum alloying, an ultraviolet beam has been used to generate free zinc atoms near an aluminum surface which was heated to the melting point with a second, visible laser beam (*19*). The Zn-Al alloy formed by mixing of adsorbed zinc in the small puddle of molten aluminum was found to be etched by acetic acid at much higher rates than the surrounding unalloyed area. This suggests that alloying could serve as a first step in selective removal of material at aluminum surfaces.

Thus there are a number of ways in which lasers can be used to modify solid surfaces on microscopic scales. These techniques are somewhat more sophisticated than the simple ablation and melting processes for which lasers have been used for some time. However, even ablation and melting operations may have a significant impact on our daily lives, as discussed in the next section.

Optical Disk Data Storage

It is clear to even the most casual observer that the data base upon which modern society relies for its smooth operation is growing at an almost overwhelming rate. Bank files, books, office memos, scientific data, and countless other collections of information are being created at rates which challenge our ability to store them. Magnetic tapes, microfilm, automated filing systems, and many other schemes have been used in an effort to devise methods for high-density storage of information in a form that leaves it readily accessible. It is also, of course, desirable that the cost of storing the information be small and that the information still be retrievable after a long storage period.

Laser recording. It has long been recognized that lasers can be used to encode information on materials that respond in an irreversible manner to exposure to high-intensity light. As a consequence of the coherence and relatively short wavelength of laser radiation, a large amount of information can be written into a very small volume of an appropriate storage medium. Of the many schemes proposed for optical information storage, however, most have exhibited serious deficiencies that render them noncompetitive with magnetic or photographic storage. In most cases, one or more of the desired features of (i) high data density, (ii) fast data accessibility, (iii) long data lifetime, and (iv) low cost were not achievable. Gradually, it became apparent that more of these features could be simultaneously realized if optical devices were combined with mechanical positioning arms similar to those used in magnetic disk systems. This marriage of optical and mechanical devices resulted in a commercially viable system, as evidenced by some of the video disk entertainment systems currently on the market. Although systems now available are adequate for home entertainment use, many data storage problems impose much more severe constraints on data error rates, archival lifetimes, and input-output rates. A number of large corporations (including RCA, Xerox, Burroughs, and 3M) as well as a growing number of smaller, more specialized ones (such as Drexler Technology Corporation and Storage Technology Corporation) are working to improve the quality and utility of optical disk devices. Many of the planned systems are in the development stage and much of the research is proprietary, but this high level of effort suggests that dramatic advances in optical disk hardware should be expected over the next few years.

The layout of a basic optical disk storage system is sketched in Fig. 4. In essence, a laser beam is focused to a diffraction-limited spot on the surface of a rapidly spinning disk. The disk is coated with a material with optical reflection properties that can be easily altered by high-intensity laser light. Data are encoded by using this process to produce track-like sequences of varying reflectivity. This is often accomplished by ablating holes or creating bubbles in the coating, although other techniques are under consideration.

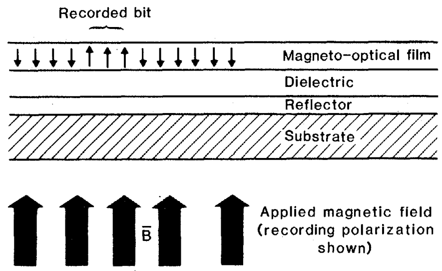


Fig. 6. Erasable magnetooptic storage medium. Information is written and erased by using a laser to locally heat the recording surface in the presence of an applied magnetic field. Domain field polarization in the magnetooptic layer is indicated. Data readout is based on the magnetooptic effect.

Data can be written in either analog or digital format. If the data are encoded in digital format, each pit or bubble in the surface coating corresponds to one bit of information. Since the laser spot size and the resulting pits or bubbles can be less than 1 μm in diameter, a very large number of bits can be written onto a small area. With a bit spacing of 1 μm approximately 10^{11} bits can be written onto a disk 14 inches in diameter. This is about the amount of information contained in 60,000 written pages. Mass-produced optical disks are expected to retail for about $20. This combination of high data density and low cost makes optical disks extremely attractive for a wide range of data storage applications.

Recording media. Although the pull of the marketplace is very strong, the problems yet to be solved are numerous. First and perhaps foremost are the difficulties associated with the stringent requirements placed on the recording medium. The recording surface must be extremely smooth and flat. Defects in the surface generate noise in the output data, as do any nonuniformities in the recording properties of the surface material. Current optical disk technology allows storage of information with an average of only one error in 10^4 to 10^5 bits. This accuracy is acceptable for most consumer entertainment applications, but for computer data processing it is desirable to have not more than one error in about 10^{12} bits. Data storage codes have been developed that allow detection and correction of the majority of errors on readout, but an error level of one part in 10^8 in the uncorrected data is still required to achieve the needed overall accuracy.

Archival storage time is another problem area. Bank records, library documents, and many other types of information often must be stored for several years. Early recording media, notably tellurium films with a low melting point, tended to degrade rapidly on exposure to the atmosphere. Data noise levels often increased dramatically after a storage period of only a few months. Application of protective overcoatings extended the storage time but did not fully alleviate the problem.

Recent research has led to a more detailed understanding of media problems, and several improved recording media are under development. Although a variety of approaches are being taken, there appears to be considerable interest in bubble-forming media or multilayer ablative media which incorporate a robust recording film protected by an overcoat (*20*) (see Fig. 5). Additional layers may also be used to optimize optical coupling between the recording film and the read-write laser. Ablative recording is conducted by evaporating pits in the recording layer with the write laser, whereas in bubble-forming media the laser heats the material in its focal region, producing outgassing, bubble formation, and a net change in optical reflectivity.

Entirely new recording media are also being evaluated. For instance, finely textured surfaces (*21*), multiphase materials (*22*), and hydrogenated semiconductor films (*23*) have been proposed and are being investigated for optical disk applications.

Advanced systems. The capability of erasing and re-recording is a desirable feature for any storage medium, although most stored information is seldom modified and a read-only medium is acceptable. Re-recordable optical disks, which use reversible optical effects for data storage, have been fabricated and may allow high-density erasable recording with further development.

An erasable system based on the magnetooptic effect is sketched in Fig. 6 (*24*). The GdCo recording film consists of a large number of magnetic domains, each of which has a residual magnetization and rotates the polarization of light passing it. If the domain field is directed away from the disk, it will rotate the polarization of the reflected light in one direction (say clockwise), and if it is directed into the disk, it will rotate the polarization of reflected light in the opposite direction (counterclockwise). The direction of the domain field can be changed by heating the GdCo film to a critical temperature and applying an appropriate external magnetic field with an electromagnet. A bit of information is recorded or erased by locally heating the recording surface with the applied magnetic field properly polarized. Since the magnetooptic effect is relatively weak and the film thickness is small, readout of the stored information requires somewhat more complex optical detection circuitry than that used in read-only systems.

Rapid manipulation of the large amount of information stored on an optical disk requires very high data input and output rates. Optical disks are well suited for parallel input-output operations in which several data channels simultaneously read from or write onto the disk. Two groups have successfully demonstrated read-write operations with an optical disk, using as many as nine optical beams in a single lens system (*25, 26*). Data flow rates as high as 400 megabits per second were achieved with this approach. Although these rates are sufficient to overwhelm almost any current computer, even higher rates may be possible with a greater degree of parallelism and simultaneous operations involving several disks.

Laser-material interactions on the scale of micrometers lie at the heart of optical disk technology. In the next section, I reverse the microscope to examine some laser-material interactions on kilometer spatial scales.

Remote Sensing

The need to identify and characterize unknown materials is encountered daily in fields as diverse as manufacturing, geophysical exploration, public health, and defense. Lasers were applied in instrumentation for measurement and analysis early on, and commercial systems for precise alignment and for range measurement have been available for many years. The sophistication of laser-based instrumentation is steadily increasing, however, and the capabilities of current systems are often quite impressive. One specific area where steady progress is being made is that of remote sensing. New hardware and new optical techniques now allow investigation of the composition as well as the size and range of a wide variety of targets, which may be located tens of kilometers from the sensing instrument. In some cases, the temperature and pressure of gaseous targets can also be probed remotely.

Lidar. Although several transmitter-receiver configurations have been employed for remote sensing, the single-ended geometry shown in Fig. 7 seems to be the most useful. This type of remote sensor is a form of laser radar or lidar. In the simplest arrangement, pulses of optical radiation from a fixed-frequency laser are directed at distant targets, and the delay and frequency shift of the return pulses are used to determine the range and velocity of the target. The relatively short wavelength of an optical radar has several important consequences: (i) it allows higher spatial resolution of the target through more accurate range gating and the use of imaging techniques, (ii) it allows spectroscopic data pertinent to the target to be gathered, and (iii) it allows returns to be obtained by Mie scattering from atmospheric aerosols in much the same way as microwave radar returns are generated by rain. Although the latter feature is used to advantage in many lidar applications, atmospheric scattering also limits the range of lidar systems.

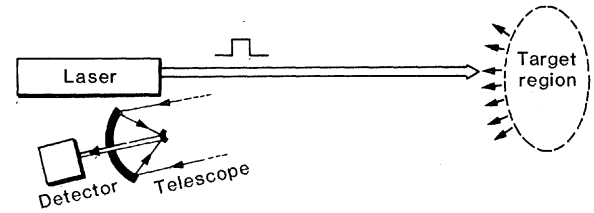


Fig. 7. Single-ended configuration for remote sensing. A pulsed laser illuminates a target region and optical return pulses generated through various scattering processes are collected by a sensitive, large-aperture receiver.

In addition to aerosol scattering, Rayleigh and Raman scattering from the gas molecules themselves can be used to generate lidar returns from gaseous targets (*27*). Since these scattering processes have very small cross sections, they are most often used in conjunction with a high-power laser source. Scattering from topographic background structures is also used to collect path-averaged atmospheric data and is particularly useful when large return signals are desired.

Single-wavelength lidar devices, which collect returns at the same wavelength from particles or surfaces, are applicable to an interesting variety of remote measurement problems. For example, the use of an airborne lidar to measure water depth has been demonstrated in rapid depth sounding of coastal waters (*28*). For these measurements a pulsed laser, operating near the blue-green peak transmission wavelength of water, is directed toward the water surface at near-normal incidence. Reflection from the surface and scattering from the sea floor are detected by a sensitive optical receiver, and the time delay between the two returns is used to measure water depth. The depth range depends on the turbidity of the water and the energy of the laser pulse. Depths up to 10 meters have been measured with a very low energy (14-microjoule) laser pulse.

Similar lidar systems have been used to monitor particles dispersed in the atmosphere. A lidar at the University of Illinois was used to obtain vertical profiles of clouds of dust from the Mount St. Helens eruption as they passed over it and to study the effect of atmospheric wind streams on those clouds (*29*). Other single-wavelength lidars have been used for applications extending from air pollution control to aircraft collision avoidance.

As laser systems grow less expensive and more compact and robust, it is likely that more measurements of position, size, and velocity will be made with lidar systems. However, an entirely new dimension in remote measurement is opened when lidar techniques are used to obtain spectroscopic information about the target. The optical absorption spectrum of a partially transparent target, for example, provides a wealth of information that can be used to pinpoint its composition. For targets of known composition, fine spectral details often can be used to measure temperature or pressure or to detect the presence of impressed electric or magnetic fields. Absorbed optical radiation also can stimulate fluorescence of the sample, with a resulting spectrum that is rich in analytic data. And at high incident light intensities nonlinear optical processes generate a host of new spectra, which reflect the composition and internal state of a material of interest.

Current laser systems usually do not have sufficient wavelength tunability to easily map out the broad absorption and reflection spectra often associated with liquids and solids. Consequently, much of the work in remote spectroscopy has focused on gas phase targets, which have sharp, well-defined spectra, or on laser-induced fluorescence spectroscopy, which can be carried out with a fixed-wavelength source.

Laser-induced fluorescence. Characterization of oil spills by use of laser-induced fluorescence (*30*) is a good example of the technique. For these measurements an ultraviolet laser and a sensitive, spectrally dispersive optical receiver are mounted in an airplane, which flies at altitudes of 100 to 1000 m above the ocean surface. The ultraviolet laser source is used to remotely induce fluorescence at a local spot on the surface of the oil slick, and a small portion of this fluorescent emission is collected by the optical receiver. Spectral and temporal analysis of the fluorescent emissions can be used not only to discriminate between oil and other chemicals, but also to classify the type of oil in the slick, that is, whether it is light refined, heavy refined, or crude oil.

Thickness of the oil slick can be deduced by monitoring variations in the laser-induced Raman emission from the water itself. The Raman effect generates light at wavelengths that are redshifted away from the laser wavelength by an amount that corresponds to the normal vibration frequencies of the water molecule, so that the origin of Raman scattered light must be predominately under the slick. Since oil strongly attenuates both the laser and Raman emissions, the thickness of the slick can be monitored from variations in the Raman signal as the aircraft flies over it. Areal extent of the slick is easily computed from the airspeed of the measurement platform.

Laser-induced fluoresence methods have also been proposed for use in uranium exploration (*31*). The fluorescent uranyl ion, UO_2^{2+}, exists in at least three types of mineralization which are amenable to remote laser sensing and which may be surface expressions of uranium deposits. The ion gives a distinctive green fluorescence spectrum when excited by optical radiation at blue or ultraviolet wavelengths and is characterized by a relatively long fluorescence lifetime. Both of these features can be utilized to separate uranyl fluorescence from spurious background signals.

Field trials on the ground have demonstrated that naturally occurring deposits of uranyl-bearing minerals can be detected with a laser-induced fluorescence system resembling those used for oil slick measurements. Extension of the technique to sensitive and rapid aerial mapping of large land areas appears feasible with some equipment modification.

Differential absorption. Single-ended, multiple-wavelength absorption measurements have been used to detect a variety of atmospheric constituents (for instance, O_3, OH, CO, NO, NO_2, and SO_2) of interest in pollution monitoring and studies of atmospheric chemistry (*27*). Scattering from aerosols or topological targets is often used to obtain returns.

Differential absorption lidars transmit two or more optical wavelengths, one of which is used to generate a reference signal and is tuned for minimal absorption by the species of interest. The remaining wavelengths are tuned to absorbing transitions of the molecule to be studied, and the differences in return signals at the various wavelengths provide information on the molecular density and detailed spectral properties of the molecule. As with other lidars, range and sensitivity are a strong function of laser pulse energy. Usable ranges of several tens of kilometers and maximum detection sensitivities of less than 1 part per million are not uncommon.

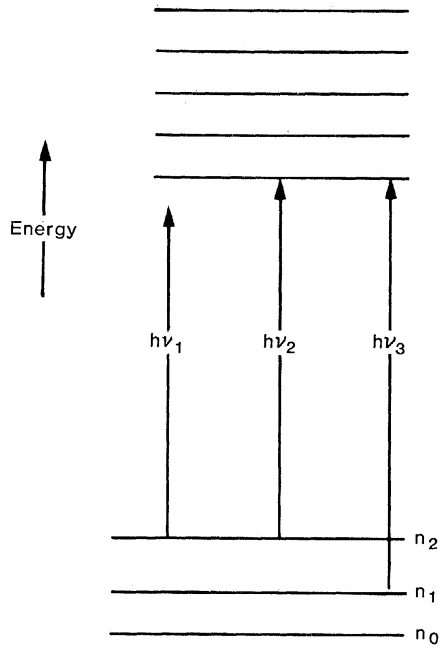


Fig. 8. Energy level diagram indicating the use of three laser frequencies to monitor two energy states of a remote molecule. Frequencies ν_2 and ν_3 monitor populations n_2 and n_1 at low-lying molecular energy states. Frequency ν_1 does not interact with the molecule and is used to generate a reference signal.

Recent work at Stanford University on simultaneous remote measurement of temperature and humidity (*32*) is an excellent example of differential absorption lidar. In these experiments a tunable, infrared laser source was used to monitor atmospheric transmission at three specific wavelengths. Two of the wavelengths overlapped absorption lines in the water vapor spectrum and were used to measure the population density of two vibrational-rotational states of H_2O (Fig. 8). The third wavelength was tuned away from any H_2O transitions and was used to generate a reference return. Since the probability that an H_2O molecule is in a particular vibrational-rotational state is a strong and well-defined function of temperature, the ratio of the return signals yields information on both the density and temperature of water molecules in the region sampled by the laser beam.

Feasibility of this technique was demonstrated by using a low-energy (5-millijoule) laser source to carry out measurements averaged over a 775-m path between the laser and a topographic scatterer. Temperatures were measured with a relative accuracy of 1.4°C and humidity with 1.5 percent relative error. Use of an improved, higher energy laser is expected to allow higher accuracy and range-resolved measurement capability.

Future Directions

The three emerging applications of lasers discussed in the preceding sections were chosen from a much larger group of activities in applied laser research and development. Future progress in application areas will be strongly influenced by the availability of laser devices and associated instrumentation. Many potential laser applications are not possible at present because laser and electrooptical hardware has not evolved sufficiently for the construction of laser and optical systems with the required features. However, laser technology is constantly undergoing refinement. The output power, tunability, stability, lifetime, monochromaticity, and spatial beam characteristics of commercial systems are steadily improving, and advanced devices are continually being introduced onto the market. With this steady evolution of commercial systems, new hardware is available for the implementation of established concepts and new concepts are being developed as more researchers are exposed to easy-to-use laser systems. It is not unreasonable to expect a continuing evolution of laser technology in the near future and a simultaneous growth in new applications of lasers.

In efforts that may strongly influence the development of laser technology in the distant future, researchers are now struggling with two difficult problems: (i) the need for coherent sources that are more broadly tunable and more efficient, and (ii) the paucity of coherent sources in the vacuum ultraviolet and soft x-ray portions of the spectrum (that is, at wavelengths less than 150 nm). Theoretical models of free electron lasers which are based on the interaction of light with an electron beam suggest that they may be capable of high-efficiency (tens of percent) generation of broadly tunable coherent radiation (*33*), but these devices are still in a very early stage of experimentation. Recent investigations of advanced frequency multiplication techniques and of potentially very short wavelength laser media also suggest that coherent vacuum ultraviolet and soft x-ray sources may one day be routinely available (*34*). Again, however, much work remains to be done. Significant breakthroughs in either of these areas would provide powerful new tools which could be expected to find many unusual applications.

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Sedimentation Field Flow Fractionation: Applications

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High-resolution separations of a wide range of inorganic and organic colloids and soluble macromolecules in the molecular weight range 10^6 to 10^{13} can be carried out by sedimentation field flow fractionation (SFFF). In SFFF, which may be characterized as a one-phase chromatographic method, separations are performed with a single, continuously flowing mobile phase in a very thin, open channel under the influence of an external centrifugal force field (*1, 2*). Sample retention takes place by the redistribution of components from fast- to slow-moving mobile phase streams near the wall of the channel because of the influence of this external force field. As a result, the SFFF method produces high-resolution fractograms similar to chromatograms, with species eluting in the order of increasing mass or particle density. Separations take place as a result of physical properties (molecular weight or mass) rather than chemical properties of the solute. Based on the molecular weight or mass information from SFFF separations, other physical properties can be deduced, including Stokes particle diameters and diffusivity (*3, 4*).

Summary. Sedimentation field flow fractionation is a powerful, new, high-resolution separation method for a wide variety of colloids, micelles, particulates, and soluble macromolecules of biological interest. Advances in instrumentation allow sedimentation field flow fractionation operation with rotor speeds up to 32,000 revolutions per minute (~ 85,000 gravities), which permits separation of materials as small as 5×10^5 molecular weight, depending on sample density. Compared to conventional centrifugation techniques, the gentle, mass-separating sedimentation field flow fractionation method is capable of higher resolution in shorter times.

For field flow fractionation (FFF) in general, the applied force field can be of any type that interacts with sample components and causes them to move perpendicular to the flow direction in the open channel. For example, the field can be a temperature gradient as in thermal FFF, electrical potential as in electrical FFF, or hydraulic potential as in cross-flow FFF (*5*). Although there is some overlap in the FFF subtechniques, they are generally complementary in potential applications (Fig. 1). Some form of FFF is generally available for the high-resolution fractionation of components in the medium to ultrahigh molecular weight range 10^3 to 10^{16}.

The most highly developed of the various FFF subtechniques is SFFF. While separating species on the basis of differences in mass, SFFF also has the highest intrinsic resolving power. It has been used for characterizing polymer latices, for both inorganic and organic colloids and pigments, viruses, liposomes, and other vesicles, and for DNA, RNA, and other polynucleotides of biochemical interest. Some biochemical applications of SFFF are given in this article. Equipment for SFFF is similar to that used in liquid chromatography except for a special channel and a means of supplying the necessary centrifugal force.

Retention in SFFF

Fractionation in SFFF results from a sedimentation equilibrium being superimposed on a steep mobile-phase velocity gradient, the combined effect of which results in a large discrimination of one particle mass from another. Separations are carried out in an open channel formed between two closely spaced concentric surfaces with a very narrow gap (for example, 0.25 millimeter) (Fig. 2a).

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